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KANSAS EVAPOTRANSPIRATION LABORATORY

ESTIMATED WINTER WHEAT YIELD FROM CROP GROWTH PREDICTED BY LANDSAT

Final Report:
Contract NAS9-14899-3S

For Period
April 1, 1977 to December 31, 1977

(E78-10112) ESTIMATED WINTER WHEAT YIELD
FROM CROP GROWTH PREDICTED BY LANDSAT Final
Report, 1 Apr. - 31 Dec. 1977 (Kansas State
Univ.) 92 p HC A05/NF A01 CSCL 02C

N78-21517

Unclas

G3/43 00112



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PREDICTED BY LANDSAT

FINAL REPORT
NAS9-14899-3S
April 1, 1977 to December 31, 1978

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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1. Report No. Final Report	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle Estimated Winter Wheat Yield from Crop Growth Predicted by Landsat		5. Report Date December 31, 1977	
		6. Performing Organization Code	
7. Author(s) Edward T. Kanemasu		8. Performing Organization Report No.	
9. Performing Organization Name and Address Evapotranspiration Laboratory		10. Work Unit No.	
		11. Contract or Grant No. NAS9-14899-3S	
12. Sponsoring Agency Name and Address NASA/JSC		13. Type of Report and Period Covered Final	
		14. Sponsoring Agency Code	
15. Supplementary Notes			
16. Abstract The work in this report covers the period from April 1, 1977 to December 31, 1977. We report here (a) estimates of leaf area index (LAI) from Landsat, (b) estimates of winter wheat yields from an evapotranspiration model, and (c) yield estimates from a growth model. Inputs to both yield models are solar radiation, temperature, precipitation, and leaf area index. Landsat data are used to estimate LAI. Yield estimates via the evapotranspiration model appear to be more promising than by the growth model. The growth model does a reasonable job of estimating head weight and total dry matter accumulation.			
17. Key Words (Suggested by Author(s)) Leaf area index, evapotranspiration, transpiration		18. Distribution Statement	
19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*

*For sale by the National Technical Information Service, Springfield, Virginia 22151

NASA - JSC

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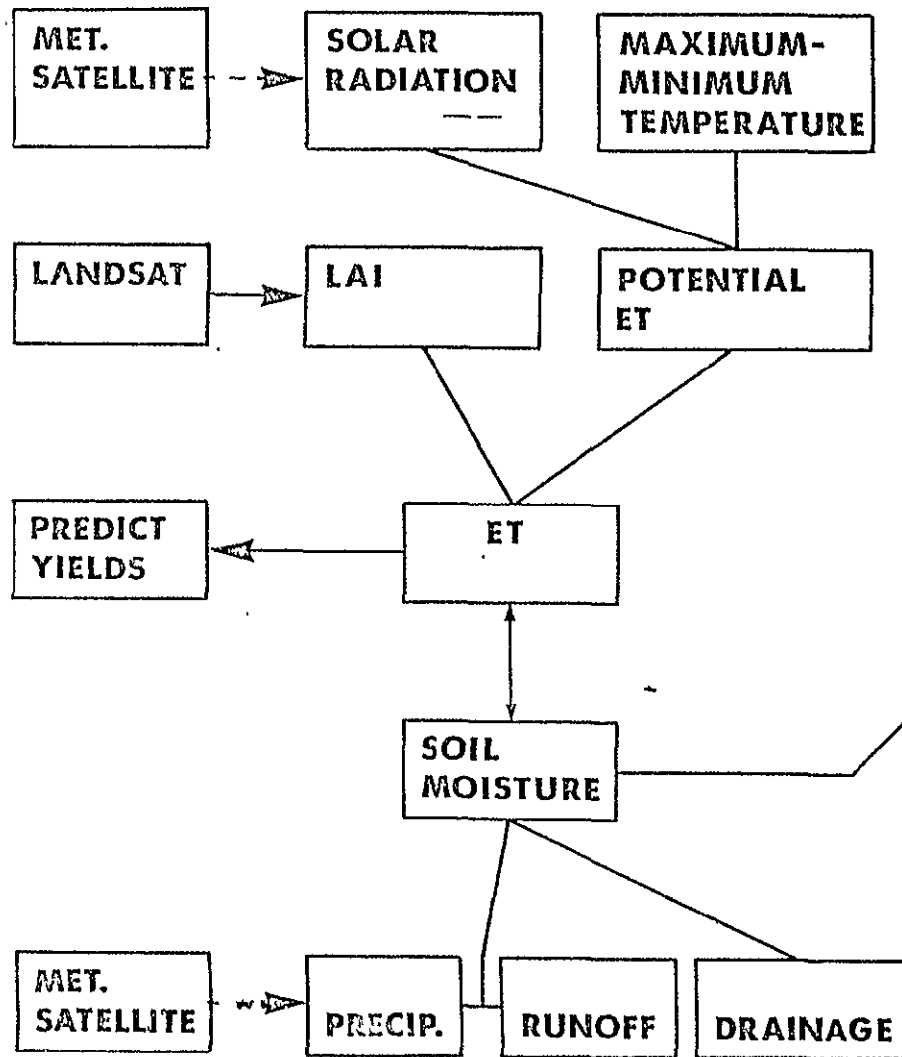
INTRODUCTION

This final report covers the period April 1, 1977 to December 31, 1977 on Contract NAS9-14899-3S.

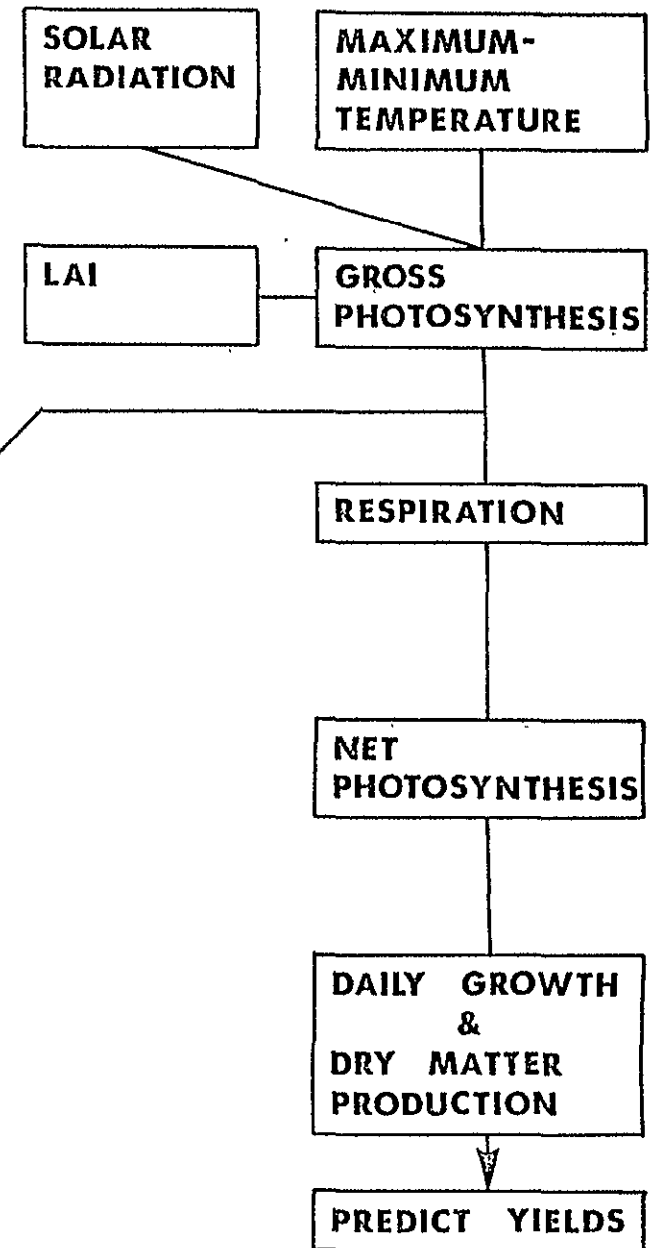
Shown in Fig. 1 is a general flow diagram of work being done on this project. The work can be divided into two parts -- an evapotranspiration model and a growth model. The end product of each is final grain yield of winter wheat. The inputs into both models are identical -- solar radiation, temperature, precipitation, and leaf area index (LAI). For the work considered here, the meteorological inputs are obtained from the National Weather Service but all have the potential for being estimated from spacecraft. Leaf area index (ratio of green leaf area to soil area) is obtained from ground and remote sensing estimates. Landsat computer compatible tapes (CCT) are used to estimate LAI.

The first chapter of this report discusses the estimates of LAI from Landsat data. The yield estimates from evapotranspiration and growth models are discussed in chapter two and three, respectively.

EVAPOTRANSPIRATION MODEL



GROWTH MODEL



CHAPTER ONE

ESTIMATING LEAF AREA INDEX OF WHEAT USING LANDSAT DATA

ESTIMATING LEAF AREA INDEX OF WHEAT USING LANDSAT DATA

Leaf area index (LAI), the ratio of the plan area of leaves to a given area of land, is a very useful measurement. It is used in estimating evapotranspiration and yield (Kanemasu et al., 1977), and is an indication of plant vigor, disease, soil salinity and moisture stress (Knipling, 1967). However, it is an expensive measurement, requiring large inputs of labor and a large number of samples when done properly. Sampling errors can be quite large especially when sampling from nonuniform crop stands.

With the launching of Landsat I in 1972 and Landsat II in 1975, a new tool is available to the agricultural community. Landsat I and II have the capability to examine the same area of land at the same local time every 18 days. The data relayed back to earth from Landsat consists of relative spectral intensity values from four wavebands from .4 μm to 1.1 μm (Table 1). The spatial resolution of Landsat is about .5 ha. Since most agricultural crop fields in Kansas are considerably larger than the spatial resolution, the spatial resolution is not a major problem; however, the temporal resolution of Landsat (18 days) is a concern in many agricultural studies. Because the MULTISPECTRAL SCANNER (MSS) data represent average values for the entire field, sampling errors are reduced. The purpose of this paper is to examine Landsat-vegetation indices that are in the literature and to correlate them to ground observations of LAI. Then, we will simulate the LAI of wheat fields employing vegetation indices.

Background. The atmosphere contains water, dust and particulate matter that vary in quantity from day to day and affect the quality and quantity of radiation detected by the MSS. A correction to the MSS measurements has been proposed for haze effects (MPAD, 1976) in which the smallest pixel value is subtracted from the other pixel values in an attempt to increase

Table 1. Spectral bands for the LANDSAT multi-spectral scanner (MSS).

Band	Wavelength (μ m)
MSS 4	0.5 to 0.6
MSS 5	0.6 to 0.7
MSS 6	0.7 to 0.8
MSS 7	0.8 to 1.1

contrast masked by the haze. Another type of correction for haze and other materials in the atmosphere is to assume all four bands are affected equally; therefore atmospheric effects are reduced by using ratios of the digital counts in each band rather than their absolute value.

Variations in the sun angle will also affect MSS measurements. Some studies attempt to normalize the MSS values by dividing each band by the sine of the solar elevation. Again this correction assumes that all MSS bands are affected similarly and band ratioing would correct sun angle effects. MPAD (1976) proposes that the sun angle has both additive and multiplicative effects for each band, the alpha values being the multiplicative effects and the beta values the additive effects. A table of alpha and beta values was developed for sun angles ranging from 20 to 75 degrees for each individual band which allows the data to be transformed to a common sun angle. Sun angle affects the amount of radiation (lower amounts at lower sun angles) and the quality of radiation seen by the MSS. At lower sun angles, the radiation must penetrate more atmosphere to reach the surface; therefore, such effects as Raleigh scattering would be greater. Row orientation of crops in conjunction with differing sun angle causes variations in the amount of shading of soil and the lower parts of the crop (Fuch et al., 1972 and Suits, 1972); however, these effects are specific to individual fields and are difficult to take into consideration.

In order to determine the vegetative properties such as LAI, the soil background must be taken into account. Wiegand and Gausman (1973) found that soils, regardless of color and moisture content, possess the same ratio between bands 5 and 7 and also between bands 5 and 6. Further, they show that on a diagram of band 5 versus band 7 (Fig. 1), all foliage data lay on one side of the soil line while water, such as lakes and snow, lay on the other side of the line. In addition, the perpendicular distance (PVI)

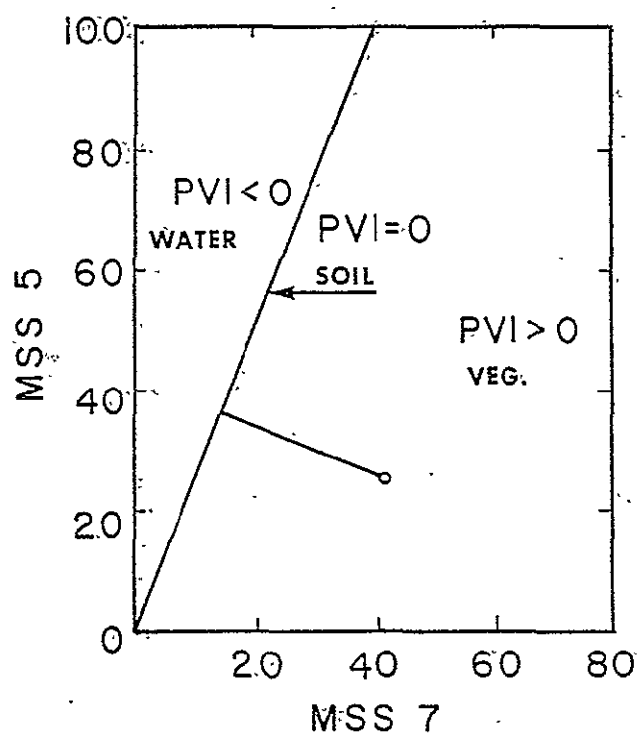


Fig. 1. Diagram of PVI (perpendicular vegetation index) showing the soil background line and the perpendicular line of a hypothetical point.

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between the soil line and the actual point under consideration is related to the foliage density. Therefore, soil effects could be effectively eliminated with the transformation,

$$PVI = [(((0.851*MSS5) + (0.355*MSS7)) - MSS5)^2 + ((0.355*MSS5) + (0.148*MSS7)) - MSS7]^2]^{.5} \quad [1]$$

$$PVI6 = [(-0.498 + (0.543*MSS5) + (0.498*MSS6) - MSS5)^2 + (2.734 + (0.498*MSS5) + (0.457*MSS6) - MSS6)^2]^{.5} \quad [2]$$

where PVI and PVI6 are perpendicular vegetative indices; MSS 5, MSS 6, and MSS 7 are the digital counts in Landsat data.

Kauth (1976) proposes another Landsat transformation in which he treats the four MSS bands as a vector. By transforming the vector with an experimentally obtained transformation matrix, the MSS data are converted into a four dimensional space -- an axis in the greenness direction, soil brightness direction, yellowness direction and an axis in a direction he calls nonsuch (Fig. 2). The transformations can be expressed by a series of linear equations,

$$\begin{aligned} \text{GREENNESS (GVI)} = \\ -0.290 \text{ MSS4} - 0.562 \text{ MSS5} + 0.600 \text{ MSS6} + 0.491 \text{ MSS7} \end{aligned} \quad [3]$$

$$\begin{aligned} \text{YELLOWNESS (YVI)} = \\ -0.824 \text{ MSS4} + 0.533 \text{ MSS5} - 0.050 \text{ MSS6} + 0.185 \text{ MSS7} \end{aligned} \quad [4]$$

$$\begin{aligned} \text{SOIL BRIGHTNESS (SB)} = \\ 0.433 \text{ MSS4} + 0.632 \text{ MSS5} + 0.586 \text{ MSS6} + 0.264 \text{ MSS7} \end{aligned} \quad [5]$$

Kauth (1976) plots MSS data for corn fields on different soils in four-dimensional space and arrived with a figure he calls a "tasseled cap" due to its shape. This theory states that the greenness, soil brightness, and yellowness of a crop may be individually separated from MSS data. Thus, the greenness value (GVI) may be strongly related to foliage density alone.

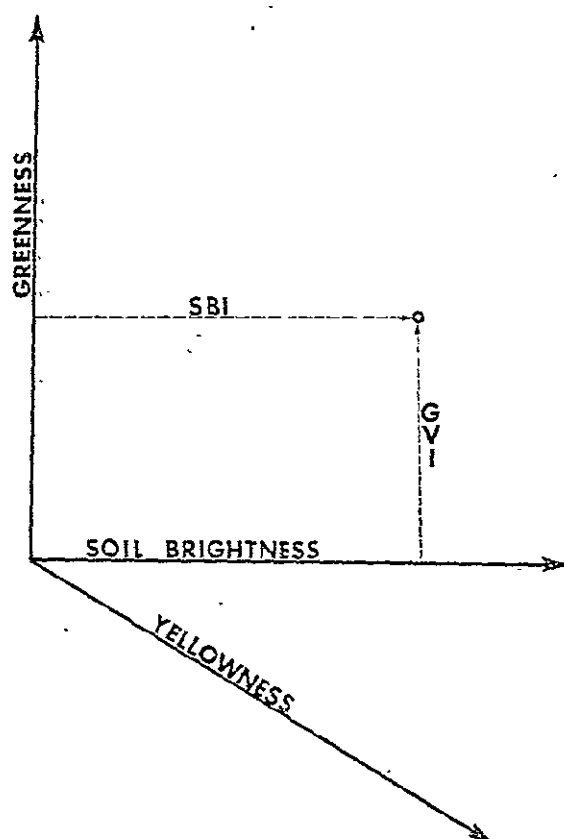


Fig. 2. A diagram of Kauth's transformation showing soil brightness; yellowness and greenness.

Rouse et al. (1973) noted a correlation between (MSS7-MSS5) and green biomass. They developed an index called TVI (Transformed Vegetative Index),

$$TVI = [((MSS7 - MSS5)/(MSS7 + MSS5)) + 0.5]^{.5} \quad [6]$$

and

$$TVI6 = [((MSS6 - MSS5)/(MSS6 + MSS5)) + 0.5]^{.5} \quad [7]$$

In order to normalize (MSS7-MSS5) they divided by (MSS5 + MSS7). The 0.5 was added to prevent the result from being negative and the square root was taken because of a better statistical correlation.

Procedure. Since the launch of Landsat I in 1972, the Evapotranspiration Laboratory has obtained Landsat data and ground measurements of LAI on several winter wheat fields in Kansas (Kanemasu et al., 1974; Kanemasu et al., 1977). Statistical correlations in MSS band ratios and LAI were performed (Kanemasu et al., 1977) and a regression equation was developed and given by

$$\begin{aligned} LAI = & 2.677 - 3.694(MSS\ 4/5) - 2.309(MSS\ 4/6) + 5.751[MSS\ 4/(2x7)] + 0.43 \\ & (MSS\ 5/6) - 2.692 [MSS\ 5/(2x7)] + 3.071 [(MSS\ 4/5) - [MSS\ 4/(2x7)]] \\ & [MSS\ 4/5]. \end{aligned} \quad [8]$$

In 1976, Kansas experienced a very cool fall which resulted in reduced growth of winter wheat throughout the fall and winter and predictions of LAI from Landsat using [8] appeared to overestimate LAI. Presumably with a larger data set (115 observations) and the use of vegetation indices, a substantial improvement could be made and provide better results at low LAI where soil effects could predominate.

Because of the large number of sources of variation involved (sun angle, atmospheric effects, LAI sampling, etc.) and the inability to quantify all of the possible sources, any practical model for estimating LAI must be empirical to some degree. Recognizing this, a linear model was developed using a statistical stepwise regression analysis. The data used consisted

of 115 observations of LAI and their respective Landsat MSS data. The various MSS band ratios and vegetation indices were individually correlated with LAI. The vegetation indices showed about the same degree of correlation with LAI (Table 2), and MSS 5/6 was the most significant of the band ratios. The best-fit model was

$$\begin{aligned} \text{CLAI} = & -0.366 - 2.265 (\text{MSS4/6}) - 0.431((\text{MSS4/5}) - (\text{MSS4/7})) \\ & (\text{MSS4/5})^{-1} + 1.745 (\text{MSS4/5}) + 0.057\text{PVI} \end{aligned} \quad [9]$$

where the $R^2 = .68$. It should be noted that MSS 4/5 appeared in [9] even though by itself it was poorly correlated to LAI (Table 2).

Shown in Fig. 3 is the comparison of observed versus predicted LAI. At low LAI there was a large amount of variation presumably due to differences in soils, increased row effects, and other factors which predominate at lower densities. However, at LAI greater than about 0.5, a better correlation between LAI and the model existed. Consequently, two models were developed -- one for low LAI and one for high LAI. CLAI [9] was employed to classify which equation to use. The low LAI equation was developed by running the statistical program on all data with observed LAI less than 0.5. The high equation was obtained similarly with the high LAI data. The resulting equations can be expressed as:

$$\begin{aligned} \text{LAI} = & 1.093 - 1.138(\text{MSS5/MSS6}) - 0.017((\text{MSS4/MSS5}) - (\text{MSS4/MSS7}))(\text{MSS4/MSS5}) \\ & - 0.016\text{PVI6} \end{aligned} \quad \text{and} \quad \text{CLAI} \leq 0.5 \quad [10]$$

$$\text{LAI} = -5.33 + 0.036\text{PVI} + 6.54 \text{TVI6} \quad \text{CLAI} > 0.5 \quad [11]$$

Equation [9] incorrectly classified 7 data points as low, which should have been classified as high and did not misclassify any observed low LAIs as high LAIs. Equation [10] performed poorly with an R^2 of only 0.3 while [11] had an R^2 of 0.6. Overall the entire method had an R^2 of .69 and is not much better than [9] alone which had an R^2 of .68. The justification for continuing to employ the 2-way classification system for predicting LAI is

Table 2.: Correlation of vegetation indices and MSS band ratios with leaf area index (LAI).

<u>R² Values of MSS Transformations:</u>			
<u>Vegetation Index</u>	<u>R²</u>	<u>MSS Band Ratio</u>	<u>R²</u>
PVI	.55	MSS 5/6	.56
PVI6	.55	MSS 5/7	.48
TVI	.50	MSS 4/7	.27
TVI6	.59	MSS 4/6	.20
GVI	.57	MSS 4/5	.10

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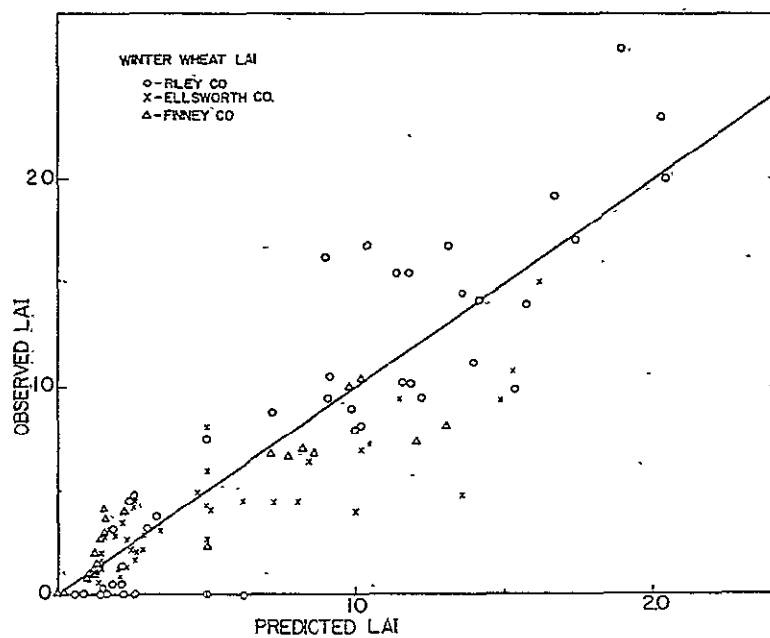


Fig. 3. Comparison of observed versus predicted leaf area index (LAI) using [10] and [11].

for the cases in which knowledge of the ontogeny of the crop (crop calendar) allows one to determine the cases in which a field is incorrectly classified. In these cases, the researcher can over-ride CLAI and the proper model can be employed. Although the procedure is empirical, the variability in both the satellite and the ground measurements allows little chance for improvement.

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CHAPTER TWO

MODELLING DAILY DRY MATTER PRODUCTION AND YIELD OF WINTER WHEAT

MODELLING DAILY DRY-MATTER PRODUCTION AND YIELD OF WINTER WHEAT

ABSTRACT

Applicability of many plant growth models are limited because of the input data requirements. Photosynthesis and respiration equations were developed from meteorological data that could easily be obtained. The single crop parameter required was leaf area index. These equations were developed for winter wheat (Triticum aestivum, (L.)) from measurement of carbon dioxide exchange rate with field chambers and an infrared-gas-analysis system. Higher gross photosynthesis rates after jointing were attributed to sink enhancement of photosynthesis. Respiration was estimated as a photosynthesis-dependent growth component and a temperature-biomass dependent maintenance component. The equations predicted dry-matter production that agreed favorably with observed dry-matter accumulation. Head weight and yield equations were developed using predicted daily growth, LAI, and meteorological variables. Improvement of yield prediction was discussed.

Key words:

Winter wheat, Gross photosynthesis, Respiration, Dormancy, Photosynthetic efficiency, Sink capacity, Yield prediction, Grain to head weight ratio, CO₂ exchange rate.

INTRODUCTION

Plant growth and yield result from the interaction of environmental factors, inherited traits of the plant, and current condition of the plant. Using models to study plant growth allows several factors to be varied at once. Models may be used to test theories of plant growth (Milthorpe and Moorby, 1974), to estimate yield, or to make crop production decisions. The simplest yield model involves summing or averaging several variables over the growing season and correlating those variables with yield by multiple regression. That approach requires a large number of crop cycles to develop a data base (Haun, 1974). More complex models may attempt to simulate individual plant processes on a daily basis (Milthorpe, Moorby and Morgan, 1974). For such models, equations to estimate daily photosynthesis and respiration are essential.

This study was designed to develop, for winter wheat (Triticum aestivum (L.)), daily growth equations estimating photosynthesis and respiration based on carbon dioxide exchange rate (CER) measurements, and attempt to estimate yield from those equations for incorporation into an evapotranspiration-growth-yield model. Our objectives were:

1. To investigate whether or not photosynthesis and respiration change as functions of growth stage.
2. To develop and test equations estimating photosynthesis, respiration, and dry-matter accumulation as functions of leaf area index (LAI) and meteorological variables.
3. To estimate yield from calculated CER values, and ontogenic and meteorological factors.

METHODS AND MATERIALS

On 25 Sept. 1975, 1 ha plots of Triticum aestivum (L.) cvs. 'Plainsman' and 'Centurk' were planted, each at seeding rates of 34 kg ha⁻¹ and 67 kg ha⁻¹ at the Evapotranspiration Research Field 14 km southwest of Manhattan in Riley county, Kansas. On 1 Oct. 1974, 5 cultivars ('Centurk', 'Tamu', 'Trison', 'Sage', and 'Arthur') were planted at the site at 67 kg ha⁻¹. On 22 Sept. 1976, eleven ¼ ha plots were planted to varieties 'Triumph', 'Eagle', and 'Plainsman'. Detailed measurements were made at the Evapotranspiration Research plots and less detailed measurements were made on commercial fields (in Riley, Ellsworth, and Finney counties) planted in late September to early October of 1974 and of 1975.

From 25 Sept. 1975 to 24 Nov. 1975, and from 1 Mar. 1976 to 15 June 1976 carbon dioxide exchange rate (CER) was measured with 4 open-chamber systems and two infrared-gas analyzers (Uras II, Intertech Corp.). Every 20 minutes each analyzer was switched between two chambers with an electronically timed, solenoid valve system, previously described by Sij et al. (1972). Each chamber enclosed an area of 1.2 m², including approximately 200 or 400 wheat plants, depending on the seeding rate; thus the CER values represented the effects of many plants. The chambers were moved to new locations at intervals (no longer than 14 days), depending on growth stage and weather. Soil was packed along the outside of each chamber to prevent large air leaks. The air circulation rate through the chambers, measured daily, was about 2.2 m³ min⁻¹ (air exchange about 1.2 times per min). In an earlier study (Kanemasu and Hiebsch, 1975) dry matter estimated from chamber measurements agreed within about 10% of observed dry matter from jointing to heading.

Based on measurements taken in the spring and fall of 1975, soil

respiration or carbon dioxide flux in $\text{mM CO}_2 \text{ m}^{-2} 12 \text{ hr}^{-1}$ from bare soil (without roots) was estimated as:

$$\text{Soil respiration} = -16.4 - 2.61 (T_{\text{MAX}} + 2T_{\text{MIN}})/3 \quad [1]$$

during the night and

$$\text{Soil respiration} = -34.34 - 1.48 (2T_{\text{MAX}} + PT_{\text{MIN}})/3 \quad [2]$$

during the day where T_{MAX} , T_{MIN} , and PT_{MIN} are maximum and minimum daily temperatures and previous daily minimum temperature in C. These equations give values ranging between those found by Kanemasu et al. (1974) during summer at the Evapotranspiration Research field ($-6.8 \text{ mM CO}_2 \text{ m}^{-2} \text{ hr}^{-1}$) and by Biscoe et al. (1975b) during spring and summer in England ($-2.5 \text{ mM CO}_2 \text{ m}^{-2} \text{ hr}^{-1}$).

The number of chambers available precluded gathering replicated CER values. The 20-minute readings were continuously recorded for each treatment for each day. Some data were discarded because of rapidly changing carbon dioxide concentration, probably caused by fluctuating atmospheric conditions (inversion with low wind). During May and June, 1976, the solenoid valve from one chamber malfunctioned.

To calculate leaf area index (LAI) and above ground dry matter accumulation we sampled plants weekly on the Riley county fields and approximately twice monthly on the Ellsworth and Finney county fields--except during December, January, and February, when samples were taken less frequently on all fields. Leaf area was measured with an optical planimeter (Lambda Instruments). From heading to approximately hard-dough stage, 0.025 was added to LAI values to account for the photosynthetic area of the heads (including awns). We measured yield by oven drying and weighing grain from three 6.1 m samples for each Riley county plot and one to three 3.05 m samples on all other fields except those in Finney county where U. S. Soil Conservation Service yield estimates were used.

Solar radiation (SR) was measured at Manhattan for the Riley county and Ellsworth county fields and at Dodge City for the Finney county fields. A thermograph was used to measure maximum and minimum temperatures at the Evapotranspiration Research field. At Garden City and Ellsworth, the National Weather Service temperature records were used.

Light interception of the canopy was measured with one sensor (Lambda Instruments) pointing upward to measure incoming photosynthetic photon flux density (PPFD), one sensor pointing down from two meters height to measure reflected PPFD (RPPFD), five sensors in parallel pointing upward at different positions underneath the canopy to measure transmitted PPFD (TPPFD), and five sensors in parallel facing downward beneath the canopy to measure PPFD reflected from the soil (RSPPFD). Intercepted PPFD (IPPFED) was calculated as

$$\text{IPPFED} = \text{PPFD} - \text{RPPFD} - \text{TPPFD} + \text{RSPPFD} \quad [3]$$

where PPFD is in micro Einsteins $\text{cm}^{-2} \text{ day}^{-1}$. One Einstein is one mole of photons. For most of the growing season, RSPPFD was small.

On fields where ontogeny data were not recorded (Ellsworth and Finney counties), stage of growth (BMTS) was estimated using a biometeorological time scale (Feyerherm and Paulsen, 1976)^{3/} (Table 1) where emergence has a value of 1, jointing of 2, heading of 3, soft dough of 4, and maturity of 5.

Because of the similarity of the pathways of photosynthesis and transpiration, the responses to water stress are similar. An evapotranspiration model for sorghum and soybean (Kanemasu, Stone, and Powers, 1976), adapted to winter wheat, was used to estimate the effect of water stress on photosynthesis. Gross photosynthesis (GP) was assumed to be reduced by a water stress factor (K_s):

^{3/}Feyerherm, A. M. and G. M. Paulsen. 1976. A biometeorological time scale applied to winter wheat. Agron. Abstr. p. 9.

Table 1. Equations used to calculate biometeorological time scale growth stages for winter wheat,
with daylength in hours and maximum temperature (Tmax) and minimum temperature (Tmin) in F.

$$V1 = C(k,1) \text{ Daylength} - c(k,0) + C(k,2) \text{ Daylength} - C(k,0)^2$$

$$V2 = C(k,4) \text{ Tmax} - C(k,3) + C(k,5) \text{ Tmax} - C(k,3)^2$$

$$V3 = C(k,6) \text{ Tmin} - C(k,3) + C(k,7) \text{ Tmin} - C(k,3)^2$$

$$\text{TDAY} = V1(V2 + V3)$$

$$\text{BMTS} = \Sigma \text{TDAY} = \Sigma V1(V2 + V3) \quad (\text{BMTS} < 2.00)$$

BMTS remains less than 2.0 until TDAY $\geq$ 0.02 10 times after BMTS > 1.95 or until $\Sigma \text{TDAY} > 2.8$.

When BMTS = 2.0, then ΣTDAY is set to 2.0.

k	Growth stage	C Matrix							
		1	2	3	4	5	6	7	8
0	Planting to emergence	10^{19}	$-.1419 \times 10^{-19}$	0	44.37	.07652	-.001571	.06875	-.001597
1	Emergence to jointing	8.413	.05581	0	23.64	-.06324	.000905	.006601	$-.771 \times 10^{-4}$
2	Jointing to booting	10.93	.02613	-.001701	42.65	.01047	0	.01396	0
3	Booting to heading	10.93	.02613	-.001701	42.65	.01047	0	.01396	0
4	Heading to soft dough	10.94	.02021	-.001192	42.18	.01688	0	.02136	0
5	Soft ripe to maturity	24.38	-.02165	0	37.67	.003543	0	.01811	0

$$K_s = \theta / .35\theta_{\max} \quad (\theta < .35\theta_{\max}) \quad [4]$$

$$K_s = 1 \quad (\theta \geq .35\theta_{\max}) \quad [5]$$

where θ is available soil water and $\theta_{\max}$ is the available soil water at field capacity.

RESULTS AND DISCUSSION

Model Development

Daily dry matter production (DMP) can be estimated from the 24 hour CER or TCER. The CER measurements were corrected for soil respiration according to [1] and [2] and integrated to obtain the 24 hour CER estimate (TCER). TCER is then the algebraic sum of the daytime CER (DCER) and the negative nighttime CER.

McCree (1974) estimated respiration for sorghum and white clover with equations of the form

$$\text{Resp} = a \text{ DCER} + b \text{ DMA} \quad [6]$$

where a is a growth coefficient and b is a temperature dependent maintenance coefficient. We estimated the nighttime CER or dark respiration (NResp) as:

$$\text{NResp} = (N_L)(-.627 - 0.0148 \text{ DNCE} - M_n \times \text{DMA}) \quad [7]$$

where NResp is the nighttime flux of CO_2 ($\text{mM CO}_2 \text{ m}^{-2} \text{ day}^{-1}$); N_L is the night length in hours; DCER is gross photosynthesis minus the daytime respiration ($\text{mM CO}_2 \text{ m}^{-2} \text{ day}^{-1}$); DMA is the accumulated above- and below-ground dry matter (gm/m^2) until maximum LAI (MLAI) is attained; thereafter DM is multiplied by LAI/MLAI. Thus, when all leaves have senesced, the maintenance component is zero. The "maintenance" coefficient (M_n) is temperature dependent and of the form

$$M_n = 10^{-6} \times (529.3 + 1.857 \times T_n + .0529 \times T_n^2) \quad [8]$$

where T_n is $(T_{\max} + 2T_{\min})/3$. $T_{\max}$ and $T_{\min}$ are the 24 hour maximum and minimum temperatures in degrees Kelvin. Equation [7] ---evaluated by using chamber measurements of DCER, night respiration, observed dry matter, and temperature data -- resulted in an $r^2 = 0.74$. The constants in [7] and [8] were determined with a multiple regression program.

Daytime respiration (DResp) can be expressed by [7] with daylength substituted for nightlength, gross photosynthesis (GP) substituted for DCER and M_d substituted for M_n . M_d is given by [8] with $T_d = (2T_{\max} + T_{\min})/3$ substituted for T_n . $T_{\min}$ is the previous daily minimum temperature in degrees Kelvin.

Table 2 compares the maintenance and growth coefficients for wheat with those of McCree's over a range of temperatures. The wheat coefficients were less sensitive to temperature than those of sorghum and white clover, probably because wheat is a cool season crop.

Gross photosynthesis (GP) depends to a large extent on the number of photons or quanta of light intercepted by the canopy. Shown in Fig. 1 is the relationship between intercepted PPFD (IPPPFD) and leaf area index (LAI). IPPFD can be expressed as

$$\text{IPPPFD} = .5739 \text{PPFD LAI}^{.3296} \quad \text{LAI} \leq 4.6 \quad [9]$$

with $r^2 = .87$ and

$$\text{IPPPFD} = .95 \text{PPFD} \quad \text{LAI} > 4.6 \quad [10]$$

where IPPFD and PPFD are given in $\mu\text{E cm}^{-2} \text{ day}^{-1}$. Estimating light interception by the point quadrants method (Wilson, 1967) while probably more accurate, would require measurement of leaf angle distribution or mean leaf angle, so was not used.

When PPFD was not measured, PPFD was estimated from daily solar radiation (SR) by the relationship

$$\text{PPFD} = 9.07 \text{SR} \quad [11]$$

Table 2. Maintenance and growth coefficients compared, for sorghum and white clover (McCree, 1974) and winter wheat (from 0° C to 30° C when daylength is 12 hours).

<u>TEMPERATURE</u>		<u>MAINTENANCE COEFFICIENTS</u>		
(C)		Sorghum	White Clover	Wheat
0		.001	.002	.0050
10		.003	.008	.0053
20		.009	.023	.0056
30		.018	.049	.0059
<u>GROWTH COEFFICIENTS</u>				
		Sorghum	White Clover	Wheat
		0.14	0.14	0.18

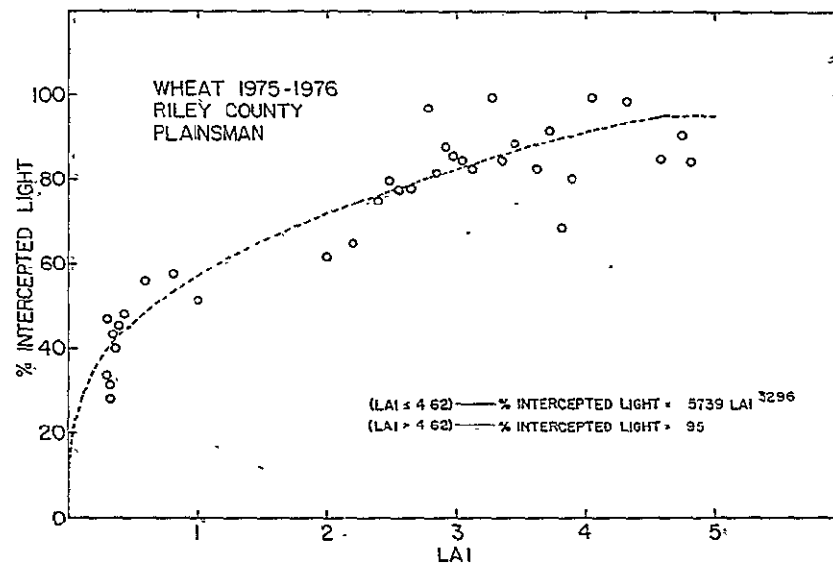


Fig. 1. Percent intercepted light plotted against leaf area index (LAI) for Plainsman V.

where SR is in ly day^{-1} . Equation [11] was obtained from SR and PPFD measurements at the Evapotranspiration Research site. Therefore, from measurements of solar radiation and LAI, intercepted PPFD can be estimated.

Gross photosynthesis (GP) is reduced by extremely hot or cold temperature. Based on our CER data photosynthesis seemed to be reduced by maximum temperatures above 23C and by minimum temperatures below 5C. For hot days, photosynthesis is decreased as T_{max} increases and air temperature increases above the critical temperature for an increased portion of the day. Also when the minimum temperature is increased for a given maximum temperature, then the portion of the day with stress increases. A high temperature stress factor is calculated as:

$$T_H = [23 - 1/2(T_{\text{min}} + PT_{\text{min}})] / [T_{\text{max}} - 1/2(T_{\text{min}} + PT_{\text{min}})] \quad [12]$$

$$\text{when } T_{\text{max}} > 23 \text{ C} \quad 5\text{C} < 1/2(T_{\text{min}} + PT_{\text{min}}) \leq 23\text{C}$$

$$T_H = 1 \quad (T_{\text{max}} \leq 23\text{C}) \quad [13a]$$

$$T_H = 0 \quad [1/2(T_{\text{min}} + PT_{\text{min}}) > 23\text{C}] \quad [13b]$$

Similarly low temperature stress increases with decreased maximum and minimum temperatures.

$$T_L = (T_{\text{max}} - 5) / (T_{\text{max}} - PT_{\text{min}}) \quad [14a]$$

$$T_L = 1 \quad (PT_{\text{min}} \geq 5^\circ\text{C}) \quad [14b]$$

$$T_L = 0 \quad (T_{\text{max}} \leq 5^\circ\text{C}) \quad [14c]$$

Temperature stress is the product of T_H and T_L :

$$T_S = T_H T_L \quad [15]$$

Potential GP (without water or temperature stress) was estimated for various growth stages by using the chamber and light-interception data. Following Biscoe et al. (1975a) monomolecular equations were used

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to estimate the photosynthetic response to intercepted light. From emergence to jointing

$$GP_p = 1000[1 - \exp(-.000276 \text{ IPPFD})] \quad [16]$$

with $r^2 = .84$, where GP_p is potential gross photosynthesis in $\text{mM CO}_2 \text{ m}^{-2} \text{ day}^{-1}$. During cold days ($T_{\text{max}} < 5^\circ\text{C}$), $GP_p = 0$ (Martin and Leonard, 1967). From jointing to maturity and $\text{LAI} \geq 1.5$,

$$GP_p = 2300[1 - \exp(-.00057 \text{ IPPFD})] \quad [17]$$

with $r^2 = .68$. If $\text{LAI} < 1.5$, [16] is used. The constants in [16] and [17] were evaluated by regression analysis. Actual gross photosynthesis is calculated as:

$$GP = GP_p \frac{K}{s} \frac{T}{s} \quad [18]$$

Table 3 illustrates the difference in photosynthesis, respiration, and daily dry matter production (DMP) (calculated by [20]) from the prejointing and postjointing photosynthesis equations. The difference in gross photosynthesis between equations [16] and [17] may be due to sink enhancement of photosynthesis (Evans and Dunstone, 1970) after jointing. GP_p was not allowed to be negative.

Estimated daily gross photosynthesis and respiration are summed in Table 4 by growth stage. Denmead (1976) estimated that a spring wheat crop had $31425 \text{ mM CO}_2 \text{ m}^{-2}$ daytime net photosynthesis and $12600 \text{ mM CO}_2 \text{ m}^{-2}$ nighttime respiration from one week before heading to 26 days after heading. For Plainsman, the values from heading to 35 days after heading were (Table 4) $9662 \text{ mM CO}_2 \text{ m}^{-2}$ daytime net photosynthesis and $-2929 \text{ mM CO}_2 \text{ m}^{-2}$ nighttime respiration. Biscoe et al. (1975a) reported $23750 \text{ mM CO}_2 \text{ m}^{-2}$ daytime net photosynthesis and $5795 \text{ mM CO}_2 \text{ m}^{-2}$ nighttime respiration for spring barley for a similar period.

Table 3. Model estimates of gross photosynthesis (GP), day and night respiration (Resp), and daily dry matter production (DMP) for a range of intercepted light values when accumulated dry matter is 500 gm/m^2 , T_m is 20°C , T_n is 15°C and daylength is 12 hour:

<u>Prejointing</u>				
<u>IPAR</u>		<u>GP^{2/}</u>	<u>Resp^{4/}</u>	<u>DMP^{5/}</u>
$\mu\text{E cm}^{-2} \text{ day}^{-1}$		$\text{mM CO}_2 \text{ m}^{-2} \text{ day}^{-1}$		gm/m^2
0	(000) ^{1/}	0	- 84	- 2.4
1814	(200)	394	-205	5.8
3628	(400)	633	-282	10.6
4535	(500)	714	-308	12.3

<u>Postjointing</u>				
<u>IPAR</u>		<u>GP^{3/}</u>	<u>Resp^{4/}</u>	<u>DMP^{5/}</u>
$\mu\text{E cm}^{-2} \text{ day}^{-1}$		$\text{mM CO}_2 \text{ m}^{-2} \text{ day}^{-1}$		gm/m^2
0	(000) ^{1/}	0	- 84	- 2.4
1814	(200)	1482	-557	27.8
3628	(400)	2009	-727	38.5
5442	(600)	2197	-788	42.4

^{1/} Intercepted light in ly day^{-1} .

^{2/} $\text{GP} = 1000[1 - \exp(-.000276 \text{ IPAR})]$.

^{3/} $\text{GP} = 2300[1 - \exp(-.00057 \text{ IPAR})]$.

^{4/} $\text{Resp} = \text{NResp} + \text{DResp}$.

^{5/} $\text{DMP} = .03 (\text{GP} + \text{DResp} + \text{NResp}) = .03 (\text{GP} + \text{Resp})$.

Table 4. Predicted gross photosynthesis (GP), daytime respiration (DResp), nighttime respiration (NResp), and net photosynthesis (TCER) in units of $\text{mM CO}_2 \text{ m}^{-2} \text{ day}^{-1}$ and dry matter accumulation (DMA) in units of gm/m^2 for Plainsman from emergence (1) to jointing (2), from jointing to heading (3), and from heading to soft dough (4), and number of days for each stage summarized.

	<u>GROWTH STAGE</u>			<u>TOTAL</u>
	<u>1-2</u>	<u>2-3</u>	<u>3-4</u>	
Days	189	36	36	260
GP	22331	57594	12022	91947
DResp	- 4444	-13972	- 2360	-20776
NResp	- 7409	- 8268	- 2929	-18606
TCER	10478	35354	6733	52565
DMA	339	1145	.218	1703

For the season (emergence to soft dough), 42.8% of the gross photosynthesis was respired which is less than estimated by Biscoe et al. (1975b) and Connor (1975) of 48.6% and 55%, respectively.

Photosynthetic efficiency values, in terms of total solar radiation (SR in ly/day), were calculated for Plainsman using the heat of combustion of plant material as 4Kcal/gm suggested by Lieth (1968) as an appropriate average for herbaceous plants. For Plainsman, values were 0.46%, 1.61%, and 0.79% respectively from emergence to jointing, jointing to heading, and heading to soft ripe. From data of Biscoe et al. (1975b) values for spring barley were 1.55% for the six weeks before anthesis and 1.00% from anthesis to soft ripe. All values were considerably below the estimate by Loomis and Williams (1963) of 5-6% for maximum possible efficiency.

The 24-hour CER or TCER can be obtained from [7], [16], [17], and [18] which require measuring solar radiation, maximum temperature, minimum temperature, and leaf area index,

$$\text{TCER} = \text{GP} + \text{DResp} + \text{NResp}. \quad [19]$$

From TCER estimates, daily dry-matter production (DMP) with 8% ash can be calculated by converting mM CO₂ to gm of carbohydrate

$$\text{DMP} = \text{TCER} \times 30/1000 \times 1.08 \quad [20]$$

where DMP is in gm/m². By summing the DMP for each day, the cumulative value can be compared with total dry matter observed in the field.

Tests

To compare the values predicted by the model with measured above-ground dry matter, we made several assumptions about root dry-matter production. Root dry weights were taken in the 1974-75 season on Centurk (Kanemasu et al., 1977). Rooting densities of 110, 180, and

250 gm/m² were obtained for dormancy, jointing and heading, respectively. Pasternak (1974), Cox and Wright (1975), and Connor (1975) found rooting densities of 230, 220, and 210 gm/m², respectively, at maturity. Those root values, added to the above-ground dry weights, were compared with those of the model for Riley county fields. Because seeding rates were lower in western than in eastern Kansas, we arbitrarily used 3/4 and 1/2 of root weights for Ellsworth and Finney counties, respectively. Fortunately, an error in estimating root weights did not result in large errors in total dry matter, especially late in the growing season.

Shown in Fig. 2 are the model-predicted dry matter and observed dry matter for all fields in which data were not used in developing the model. In general, the values lie along the 1:1 line.

Shown in Figs. 3, 4, and 5 are the temporal trends in observed and predicted dry matter and leaf-area index. Shown in Fig. 3 are predicted and observed dry matter for Evapotranspiration Research fields. Predicted and observed dry matter agreed closely until heading (1 May), when the equations began to underestimate dry-matter accumulation. The NCE measurements also decreased after heading as LAI decreased. That discrepancy, which did not occur on the commercial fields studied (Figures 2, 4, 5), might have resulted from errors (1) in sampling dry matter; (2) in measuring NCE after jointing; (3) errors associated with photosynthesis by yellowing leaves (not included in LAI measurements); or (4) in estimating respiration after heading. After a severe frost (3 May), the chambers might have been moved to locations with greater head damage than the dry matter samples.

No CER measurements were made during December, January, or February;

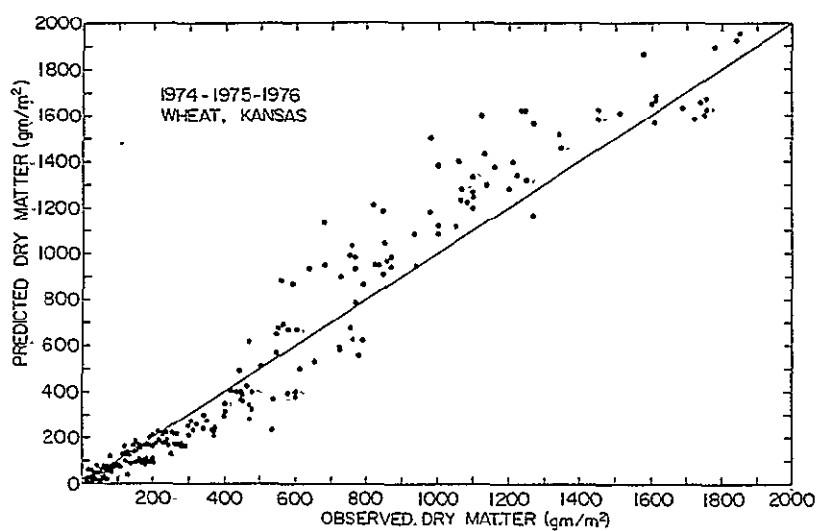


Fig. 2. Observed versus predicted dry matter accumulation for 15 fields.

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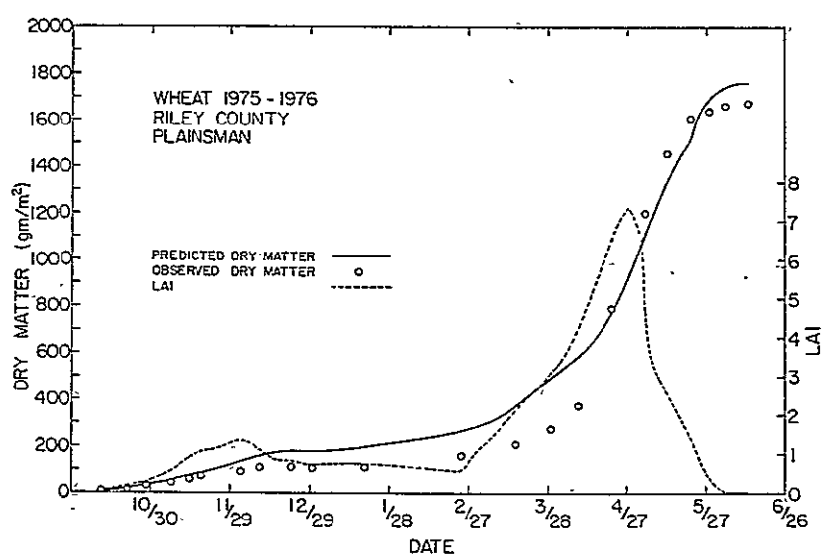


Fig. 3. Seasonal trends in observed and predicted dry matter accumulation and LAI for Evapotranspiration Research fields (1975-1976).

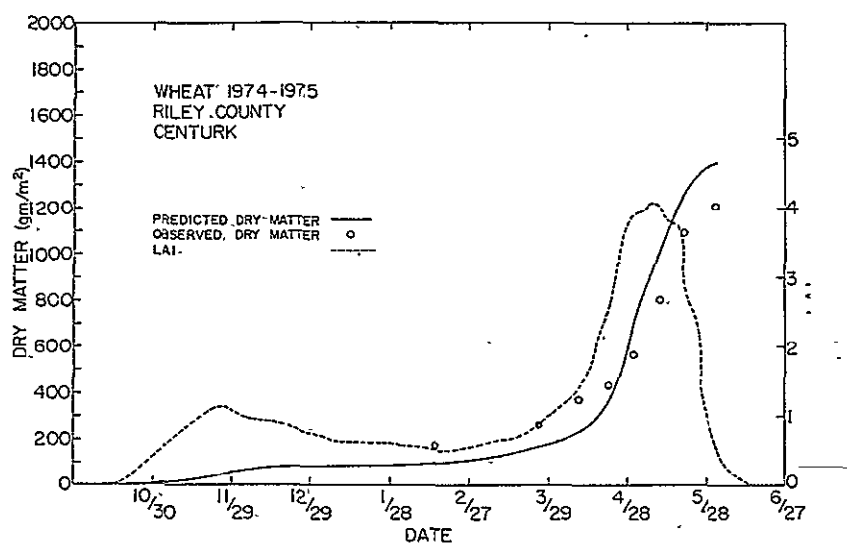


Fig. 4. Seasonal trends in observed and predicted dry matter accumulation and LAI for a Riley county field (1974-1975).

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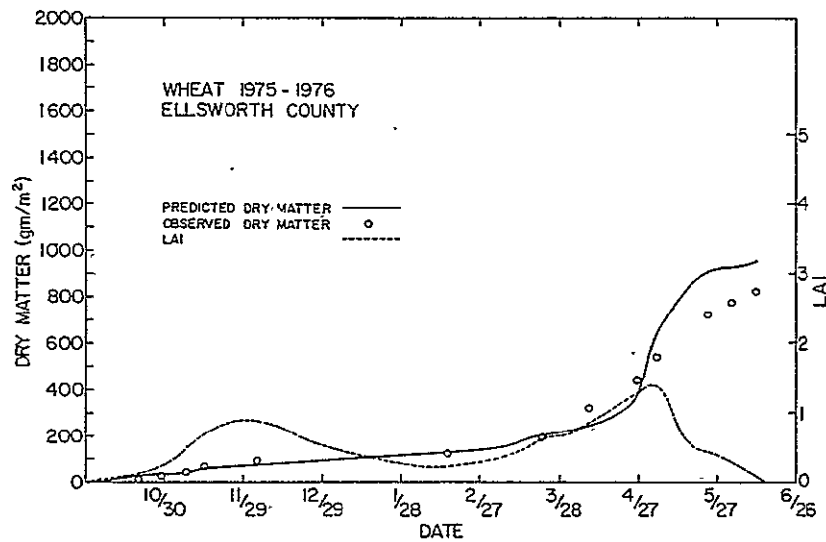


Fig. 5. Seasonal trends in observed and predicted dry matter accumulation and LAI for an Ellsworth county field (1975-1976).

hence, we could not evaluate directly the assumption that photosynthesis ceases when the maximum temperature is less than 5 C. However, the predicted dry matter at the end of February was not greatly different from the observed dry matter (Figs. 2, 3, 4, 5). Repka and Kubova (1971) reported that roots and shoots of wheat respond rapidly to temporary increases in temperature.

We could not adequately test the assumption that GP decreases linearly with available soil moisture after a threshold value because water deficits did not occur until the ripening period. At that time, GP was also declining because of leaf senescence.

Yield Process

Carbohydrate enters the grain from carbon fixed in the leaves or head during the grain-filling period or from carbon fixed earlier and released for translocation to the head during senescence (Lupton, 1972). Although yield is influenced by the number of culms per area of field, determined during fall and spring tillering, yield formation actually begins with head formation at ear initiation (jointing), when the potential number of seed-bearing tillers and number of seeds per head are set.

Five types of factors may be regarded as limiting yield, of which three (2, 3 and 4) are considered in the model.

- 1) Sink capacity is set by tillering, panicle initiation, and flowering. Very high or low tiller number per area may be partly compensated by the percent of tillers forming heads and by the number of seeds per head. Stress during tillering, jointing, or flowering may reduce sink (Halse and Weir, 1974; Gifford, 1977). Sink capacity, then, may be defined as $\text{heads/m}^2 \times \text{seeds/head} \times \text{potential weight/seed}$.

- 2) Sources contributing to grain filling are TCER after jointing and translocation of carbon. TCER is calculated as a function of intercepted light, temperature, growth stage, water stress, and temperature stress. Carbon released is estimated from decrease in LAI (reflecting senescence of leaves, sheaths, stems, and roots).
- 3) Translocation rate of carbon from leaves and stems into the grain may be limited by high temperature stress (Asana and Basu, 1963).
- 4) Duration of the grain-filling period is estimated in the model from daylength, light intensity, and temperature by a biometeorological timescale^{4/} (Table 1) but varietal differences are not considered.
- 5) Damage to the crop during grain-filling due to biological or mechanical factors (pests, hail, flooding) is not considered.

When sink capacity is not limiting, then rate of supply of the sources, rate of movement into the grain, and duration of the grain-filling period determine yield.

Yield Equations

Head weight increases slowly from jointing until shortly after anthesis; thereafter it increases rapidly in weight as the grain is filled. Summarized in Table 5 are changes in head weight and LAI during several periods from jointing to maturity, and TCER during each period, for 11 plots at the Evapotranspiration Laboratory Research site in 1977.

^{4/} Feyerherm, A. M. and G. M. Paulsen. 1976. A biometeorological time scale applied to winter wheat. Agron. Abstr. p. 9.

Table 5. Summary of changes in head weight, total weight, and LAI for the Riley county fields used to develop yield equations and coefficients derived for the yield equations.

Stage		2.0 - 2.7 ^{1/}		2.7 - 3.0 ^{2/}			3.0 - 5.0 ^{3/}			
Variety	Plot	Head Growth	Total Growth	ΔLAI ^{4/}	Head Growth	Total Growth	ΔLAI ^{4/}	Head Growth ^{5/}	Total Growth ^{6/}	DMA ^{7/} ₄
		(gm/m ²)		(gm/m ²)			(gm/m ²)			(gm/m ²)
Triumph	ET Lab T1	20	136	.19	30	18	.41	292	90	387
Triumph	ET Lab T2	20	273	.34	20	19	.84	275	104	538
Triumph	ET Lab T3	20	183	.33	30	19	.67	327	84	433
Eagle	ET Lab E1	20	284	.28	30	19	.92	361	98	650
Eagle	ET Lab E2	20	350	1.14	70	96	.54	258	86	755
Eagle	ET Lab E3	20	257	.35	20	19	.70	327	93	617
Eagle	ET Lab E4	20	173	.15	30	14	.16	292	70	506
Plainsman	ET Lab P2	30	82	.35	30	18	.38	275	71	385
Plainsman	ET Lab P3	50	83	.42	20	18	.39	327	69	385
Plainsman	ET Lab P4	40	83	.32	30	18	.44	292	74	390
n.a.	Puett	20	415	.31	50	87	1.36	293	136	763
Σ		280	2319	3.54	360	345	6.45	3319	975	4980
Coefficient		.13			.71			1.00		.41

^{1/} Jointing to booting stage.

^{2/} Booting to heading stage.

^{3/} Heading stage to physiological maturity.

^{4/} ΔLAI values are limited to ≤ 1.00 in any period for calculating head growth coefficients.

^{5/} Divided by $\overline{Ts}_5$ (average temperature stress from heading to physiological maturity) to correct for effects of temperature stress.

^{6/} Total growth is limited to $\leq 300 \text{ gm/m}^2$ for calculating coefficient.

^{7/} DMA at 4.0 is limited to $\leq 500 \text{ gm/m}^2$ for calculating coefficient.

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Assuming sink capacity is not limiting, head weight is calculated as:

$$\text{Head Weight} = 1.08 \left[.13 \left(\sum_{2.7}^{2.7} \text{TCER} \frac{30}{1000} \right) + .71 \left(\frac{\Delta \text{LAI} \times \text{SLW}}{2.7} + \sum_{2.7}^3 \text{TCER} \frac{30}{1000} \right) + \right. \\ \left. \left({}_3\overline{\text{Ts}}_5 \right) \left(\frac{\Delta \text{LAI} \times \text{SLW}}{3} + \sum_3^5 \text{TCER} \frac{30}{1000} + .15 \text{DMA}_4 \right) \right] \quad [21]$$

with $r^2 = .72$, where 1.08 adds 8% ash; $\sum_a^b \text{TCER} \frac{30}{1000}$ is total CO_2 exchange

rate of the crop from stage a to stage b, converted to carbohydrate; $\Delta \text{LAI} \times$

SLW is decrease in LAI from stage a to stage b times the specific leaf weight (45 gm/m^2 ; Puckridge and Donald, 1967); ${}_3\overline{\text{Ts}}_5$ is average temperature stress from stage 3 to stage 5; and DMA_4 is total dry matter accumulation up to stage 4. $\Delta \text{LAI} \times \text{SLW}$ is used to approximate carbon released by senescence of leaf sheaths, stems, and roots as well as leaves. To prevent overestimation of yield (possibly when sink is limiting) change in LAI was limited to $.5 \text{ m}^2/\text{m}^2$ from stages 2.7 to 3.0 and to $1.0 \text{ m}^2/\text{m}^2$ from stages 3.0 to 5.0, $\text{TCER} \frac{30}{1000}$ was limited to 150 gm/m^2 from stages 2.7 to 3.0 and to 300 gm/m^2 from stages 3.0 to 5.0, and DMA_4 was limited to 500 gm/m^2 .

Temperature stress during grain-filling may affect yield by reducing sugar translocation from the stem into the head as well as by reducing the photosynthesis rate (Asana and Basu, 1963). Ruckebauer (1975) suggested that translocation rate into the grain is dependent upon the capacity of grain to store carbohydrate. So temperature may limit grain growth by reducing the starch synthesis rate in the grain.

Grain and head weights for winter wheat and spring wheat from several sources are compared in Fig. 6 and in Table 6 with references. Most of the data from the literature lie close to the .74 grain/head ratio. Some of the points with lower ratios can definitely be attributed to late

Table 6a. Comparison of grain and head weights for several spring and winter wheat fields reported in the literature.

<u>Reference</u>	<u>Species</u>	Grain	Head	<u>Ratio</u>
		$\frac{Wt_2}{(gm/m^2)}$	$\frac{Wt_2}{(gm/m^2)}$	
Puckridge and Donald, 1967	Spring	46	65.2	.71
		173	236	.73
		247	342	.72
		234	299	.78
		185	249	.76
Spiertz, 1974	Spring	801	1124	.71
Pearman, Thomas, and Thorne, 1977	Spring	481	650	.74
		514	685	.75
		444	600	.74
Paltridge et al., 1975	Winter	281.6	360.9	.78
Paltridge et al., 1972	Winter	401.0	627.1	.64

Table 6b. Comparison of grain and head weights for several Kansas winter wheat fields.

County	Field	Variety	Year	Grain	Head	Ratio
				Wt	Wt	
				(gm/m ²)		
Riley	Lysimeter Low	Plainsman	1976	195	660	.30
	ET Lab Low	Centurk	1976	306	700	.44
	ET Lab Med	Centurk	1976	339	680	.50
	ET Lab High	Centurk	1976	289	680	.43
	Cedarburg	n.a.	1976	183	470	.39
	Puett	n.a.	1976	174	480	.36
	ET Lab T1	Triumph	1977	165	210	.78
	ET Lab T2	Triumph	1977	159	220	.71
	ET Lab T3	Triumph	1977	183	200	.91
	ET Lab T4	Triumph	1977	110	190	.57
	ET Lab E1	Eagle	1977	208	260	.80
	ET Lab E2	Eagle	1977	183	240	.76
	ET Lab E3	Eagle	1977	183	210	.88
	ET Lab E4	Eagle	1977	153	210	.74
	ET Lab P1	Plainsman	1977	128	200	.65
	ET Lab P2	Plainsman	1977	147	220	.67
	ET Lab P3	Plainsman	1977	183	250	.73
	ET Lab P4	Plainsman	1977	165	220	.76
	Cedarburg	n.a.	1977	242	400	.61
	Puett	n.a.	1977	164	250	.66
Finney	18	n.a.	1977	206	419	.49
	46	n.a.	1977	167	225	.74
	50E	n.a.	1977	153	440	.35
	94	n.a.	1977	162	290	.56
	129	n.a.	1977	185	481	.38
	186	n.a.	1977	240	360	.67

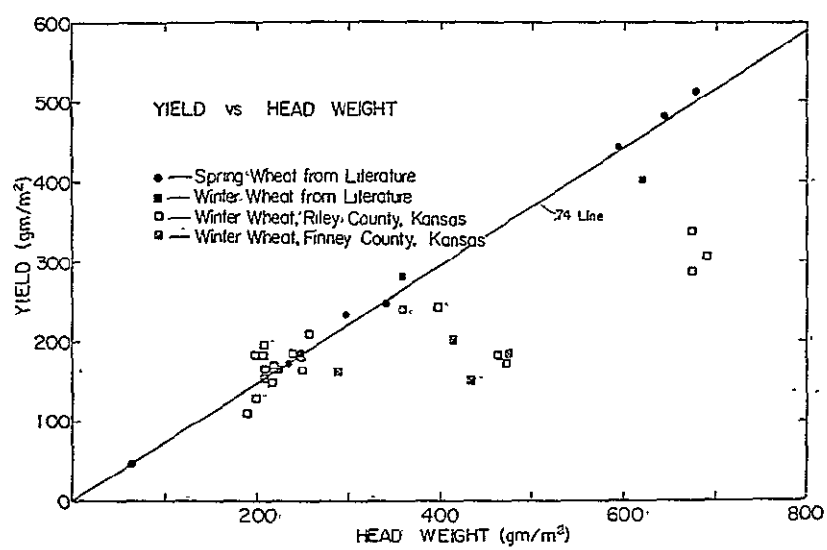


Fig. 6. Comparison of grain and head weights for several wheat crops.

frosts (Lysimeter, 1976), flooding during grain-fill (Plainsman 1, 1977), and fertilizer burn (Triumph 4, 1977).

Predicted yields, calculated as

$$\text{Yield} = .74 \times \text{Head Weight} \quad [22]$$

with $r^2 = .41$ are plotted against observed yields in Fig. 7 and listed with observed yields and observed and predicted head weights in Table 7.

To improve the method of yield prediction outlined in this paper, we need information in several areas. Tillering occurs in response to light, temperature, population density, nutrients, and previous growth of the crop with different varieties responding differently to these conditions. Spikelet initiation and possibly seed setting are affected by temperature stress (Halse and Weir, 1974), shading (Pepper and Prine, 1972), and reduced leaf area (Davidson, 1965), at jointing and at anthesis. The greater variation in the grain/head weight ratio of wheat crops in Kansas than that of other wheat crops reported in the literature (Table 6) may be due to high temperatures in Kansas in early summer. The different varieties planted in 1975, 1976, and 1977 in Riley county had jointing and heading dates different by as much as 6 days (Table A27 in Appendix A), differences not reflected in the biometeorological timescale.

CONCLUSIONS

The maintenance coefficient of wheat presented here was less sensitive to temperature than were coefficients found for sorghum and white clover (McCree, 1974), possibly because wheat is a cool-season grass. Photosynthesis was found to increase sharply after jointing possibly because of increased sink capacity. On most wheat fields studied, predicted and observed dry matter agreed for most of the growing season. Assuming that photosynthesis ceased when the maximum temperature was less than 5°C gave

Table 7. Listing of observed and predicted yields and head weights for several Kansas wheat fields.

<u>County</u>	<u>Field</u>	<u>Variety</u>	<u>Year</u>	<u>Obs</u> <u>Yield</u>	<u>Pred</u> <u>Yield</u>	<u>Obs</u> <u>Head</u>	<u>Pred</u> <u>Head</u>
				(gm/m ²)			
Riley	ET Lab 1	Centurk	1975	280	431	n.a.	582
Riley	ET Lab 2	Sage	1975	206	439	n.a.	593
Riley	ET Lab 3	Tamu	1975	227	426	n.a.	575
Riley	ET Lab 4	Trison	1975	298	436	n.a.	589
Riley	ET Lab 5	Arthur	1975	297	424	n.a.	573
Riley	Lysimeter	Cloud	1975	268	436	n.a.	589
Riley	Lysimeter Low	Plainsman	1976	195	376	660	511
Riley	ET Lab Low	Centurk	1976	306	343	700	463
Riley	ET Lab Med	Centurk	1976	339	436	680	590
Riley	ET Lab High	Centurk	1976	289	345	680	466
Riley	Cedarburg	n.a.	1976	183	254	470	343
Riley	Puett	n.a.	1976	174	292	480	394
Riley	T 1	Triumph	1977	165	153	210	207
Riley	T 2	Triumph	1977	159	209	220	282
Riley	T 3	Triumph	1977	183	174	200	235
Riley	T 4	Triumph	1977	110	160	190	217
Riley	E 1	Eagle	1977	208	210	260	280
Riley	E 2	Eagle	1977	183	252	240	341
Riley	E 3	Eagle	1977	183	200	210	270
Riley	E 4	Eagle	1977	153	161	190	217
Riley	P 1	Plainsman	1977	128	160	200	216
Riley	P 2	Plainsman	1977	147	142	220	192
Riley	P 3	Plainsman	1977	183	143	250	193
Riley	P 4	Plainsman	1977	165	145	220	196
Riley	Cedarburg	n.a.	1977	242	372	400	502
Riley	Puett	n.a.	1977	164	269	250	364
Ellsworth	E. Zeman	n.a.	1976	176	190	n.a.	257
Ellsworth	A. Zeman	n.a.	1976	302	343	n.a.	463
Ellsworth	Wm. Bartunek	n.a.	1976	335	234	n.a.	316
Ellsworth	E. Zeman	n.a.	1977	293	290	n.a.	392
Ellsworth	A. Zeman	n.a.	1977	116	278	n.a.	375
Ellsworth	Wm. Bartunek	n.a.	1977	331	363	n.a.	490
Colby	19	n.a.	1976	184	261	n.a.	353
Colby	20	n.a.	1976	268	394	n.a.	532
Colby	29	n.a.	1976	244	375	n.a.	506
Colby	17	n.a.	1977	159	348	n.a.	470
Colby	19	n.a.	1977	232	306	n.a.	413
Colby	20	n.a.	1977	226	347	n.a.	468
Finney	18	n.a.	1977	206*	195	419	263
Finney	46	n.a.	1977	167*	193	225	261
Finney	50E	n.a.	1977	153*	335	440	453
Finney	129	n.a.	1977	185*	278	481	376
Finney	186	n.a.	1977	240*	199	360	269

*SCS estimates.

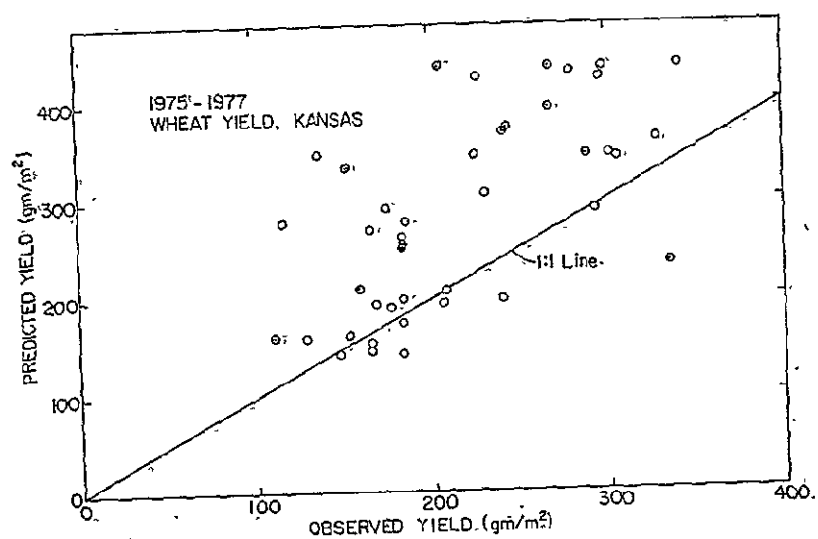


Fig. 7. Observed versus predicted yield for several wheat crops.

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reasonable estimates of dry-matter accumulation during the winter.

Equations were developed to estimate wheat yield from growth model input and output data. Reasons for the poor yield prediction of the equations were discussed.

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CHAPTER THREE

TRANSPARATION-BASED WINTER WHEAT YIELD MODELING IN DIVERSE ENVIRONMENTS

TRANSPIRATION-BASED WINTER WHEAT YIELD MODELING IN DIVERSE ENVIRONMENTS

ABSTRACT

A modification of the long-standing evapotranspiration (ET)/yield relationship is proposed for winter wheat yield modeling. The model is based on output data from a comprehensive ET model that has been developed and tested for several locations. Data included two years of yield and ET information from sites across the state of Kansas. The yield model performed favorably in predicting yields across Kansas for the 1977 crop year, for a site in Texas, and under conditions of induced diverse conditions by chlorocholine chloride (CCC). Advantages of this modeling approach include limited input data, simplicity of quantifying terms, and proven capability. Disadvantages include lessened accuracy at high soil moisture levels, requires estimates of leaf area index and plant ontogeny. The model should prove useful where water remains the major limiting factor in wheat production.

TRANSPIRATION-BASED WINTER WHEAT YIELD MODELING IN DIVERSE ENVIRONMENTS

INTRODUCTION

The ability to ascertain the yield of a crop by computer simulation (e.g. systems analysis) techniques has intrigued agronomists, economists and agribusinessmen alike for many years. The scientist is often fascinated by the end results of systems techniques, a better conceptual view of the systems or mechanisms by which a plant determines its yield. The economist or agribusinessman is interested because crop prices (and associated market and futures profits) are directly affected by official declarations of predicted world yields. Computer simulation, coupled with remotely-sensed satellite imagery, offers a valuable tool to predict world yields with limited environmental information. The current world food and fiber situation with its Malthusian shortages, climatic stresses, etc., give additional impetus to the formulation of operational yield simulation systems.

One method for predicting relative yields that has been given varied response for many years utilizes evapotranspiration/yield (or more correctly, transpiration/yield, as we shall show later) relationships. The direct linear relationship between yield and evapotranspiration (ET) was first comprehensively documented by Briggs and Shantz (1913). Since that time, the literature has been replete with both supportive and skeptical reviews. A few of those that are directly related to this report are the positive aspects shown by DeWit (1958), Arkley (1963), Stewart (1972), and Hanks (1974). Rawitz (1970) showed data that indicated the relationship between ET or T (transpiration) and yield is not completely linear or correlated, especially at high water levels. There are others who question the relationship vigorously, but this is not well documented in the literature.

We currently have a computerized ET model at the Evapotranspiration Laboratory that is operational for a number of sites across Kansas and the Great Plains. The model is designed so as to accept satellite sensed crop data (leaf area index, LAI). LAI measurements give the model a dynamic response to crop growth and allow the splitting of ET into its individual components of transpiration (T) and soil evaporation (E).

We wished to know whether winter wheat yields could be predicted with reasonable accuracy, utilizing the comprehensive output data of this ET model. A yield estimate based upon physical quantities and simulated crop responses was preferred over a purely statistical approach that is not truly dynamic in its response to changing crop conditions. The question to be answered was simple: we have the ET data -- can it be used to predict yields over wide areas and diverse environments?

THEORY

Evapotranspiration and Yield--Dry Matter

The rationale of ET based yield models of the past has been that the processes of biomass synthesis and translocation are closely related to the transpiration pathways within the plant (Boyer and McPherson, 1975), thus, we expect that translocation cannot proceed without transpirative flow and that the metabolic rates would follow the transpirative response to water stress. Further, we anticipate that the critical processes of photosynthesis and CO₂ gas exchange will be directly correlated to rates of water vapor loss at the stomates, as DeWit (1958) suggested. The correlations are indeed complex and not fully linear; however, the large portion of reported data would be supportive that yield is highly correlated to plant-soil-water relations. To the extent that water is limiting, T/Yield relationships must be employed to adequately predict yield. In Kansas, and throughout

much of the world, water relations are the major limiting factors in crop production.

A mathematically-sound expression of the transpiration/yield relationship was given by Hanks (1974) as:

$$Y/Y_p = T/T_p \quad [1]$$

where Y is actual dry matter yield, Y_p is the dry matter yield when water is not limiting, T is the actual transpiration sum, and T_p is the potential transpiration sum if soil water was not limiting. Note that any limiting factors other than water will be accounted for in the Y_p term that must be determined for the given site conditions and year. This is a simple expression of the direct limiting influence of water stress on yield.

This equation has applicability only under conditions of differential water stress and is not intended to model any or all of the many variables that can be included in the Y_p term. Hill, et al. (1974) showed the value of this approach for irrigation management problems.

Most investigators, previous to Hanks (1974), correlated yield with ET rather than T because in actual field conditions, ET cannot be measured separately as E and T. Because soil evaporation is seldom constant or negligible in grain crops, the combining of E with T must surely introduce an error term into the yield relationship. With energy balance, the evaporation from the soil surface and from the plant can be evaluated separately (Ritchie, 1972); thus, equation (1) can be evaluated with reasonable accuracy.

Evapotranspiration and Yield--Grain

The processes that govern grain formation within the plant are much more complex than those producing dry matter (biomass). For example, a

wheat crop may have a lush vegetative appearance, yet have little grain at harvest. It is agreed that in determinate crops such as wheat, certain stages of growth are more crucial in transpiration/yield relations than others (e.g. flowering and grain filling). This has been documented in excellent reviews such as that of Boyer and MacPherson (1975). Hanks (1974) revised an equation of Jensen (1968) to include relative transpiration, rather than relative evapotranspiration:

$$Y/Y_p = \prod_{i=1}^n (T/T_p)^{\lambda_i} \quad [2]$$

where Y is actual grain yield, Y_p is grain yield if water is not limiting, i is a phenological stage of growth, T is actual transpiration for that stage of growth, T_p is potential transpiration for that stage if water is not limiting, and λ is an exponential weighting factor.

Equation [2] has been shown accurate for corn (Hanks, 1974; Hill et al., 1974) and spring wheat (Rasmussen, 1976) under conditions of differential water stress; therefore, it is an extremely useful approach in irrigation management studies. However, Y_p must be determined for each variety and locale on a yearly basis especially if the length of the phenological stages vary.

Evapotranspiration Model

Kanemasu, et al. (1976) described a versatile ET model that has been developed in computerized form. The model uses inputs of daily solar radiation, LAI, maximum temperature, minimum temperature, and water received (precipitation and irrigation), to compute daily values of soil evaporation (E), transpiration (T), potential E and T, and a detailed ledger of the water balance within the soil profile. Season inputs are soil profile characteristics such as water holding capacity and surface

drying characteristics. This model has been shown to be effective for soybean and sorghum (Kanemasu, et al., 1976) wheat (Kanemasu, et al., 1977), and corn (Rosenthal, 1977).

This model is initiated with a layered soil profile of known water content and water holding/loss characteristics. Each day the energy available for water loss is evaluated with the modified Priestley-Taylor equation as described by Tanner and Jury (1976). Soil evaporation and crop transpiration are evaluated separately. Surface soil evaporation is allowed to proceed at its potential rate during the day following an addition of water (rain or irrigation). After the soil has lost a certain amount of water, E decreases with the square root of time until the soil reaches an air dry lower limit or more water is added. Transpiration proceeds at a potential rate until 65% of the soil's available water is depleted, and then decreases linearly to zero at the permanent wilting percentage (PWP). The energy is partitioned between the evaporation and transpiration processes according to the LAI.

YIELD MODEL DEVELOPMENT

We desired a model that would respond to the differing conditions of the growing season throughout the Great Plains. Differential water stress is the most likely limiting factor to wheat yield in this wide area. However we realized that water is not often limiting in the eastern belt of this region where annual precipitation approaches 100 cm. A small data set from throughout Kansas for two years (see Table 1) was assembled for model formulation.

The growing season was separated into three phenological periods: emergence to jointing (approximately October to March in Kansas), jointing to heading (approx. March to May), and heading to soft dough (approx. May to June). This separation allowed the period of rapid vegetative growth (jointing to heading) and rapid grain filling (heading to soft dough) to be evaluated independently. Phenological development was modeled using a modified form of the Robertson Biometeological Time Scale (Feyerherm and Paulsen, 1976).

The output of the ET model was programmed to show the following quantities evaluated for each phenological stage and for the entire season (see Table 2). These summational relationships will be referred to by number as model development is discussed.

Hanks (1974) and Hill et al. (1974) used relationship #4 in Table 2, in their multiplicative grain model for corn. However, the λ values were determined by empirical (trial and error and experience) means. We desired a more quantitative approach. Regression-type models were readily available as statistical packages for computers and programmable calculators; thus, initially a simple additive multiple linear regression model was tested. The square of the Pearson product-moment correlation (R^2) for

Table 1. Summary of components of calibration data set.

Calibration data set1974-1975

Ashland, Riley County, Kansas

5 varieties on intensive E.T. Lab site
(Centurk, Arthur, Sage, Tamu, & Trison;
with yields averaged to one value per variety)

3 cooperating farm sites (one ave. yield value per site)

Ellsworth County, Kansas

3 cooperating farm sites (one ave. yield value per site)

Finney County, Kansas

3 cooperating farm sites (one ave. yield value per site)

TOTAL: 14 observations

1975-1976

Ashland, Riley County, Kansas

3 planting densities of Plainsman V variety
(one ave. yield value per density)

3 cooperating farm sites (one ave. yield value per site)

Thomas County, Kansas

3 cooperating farm sites (one ave. yield value per site)

Ellsworth County, Kansas

3 cooperating farm sites (one ave. yield value per site)

TOTAL: 12 observations

Table 2. Normalized actual/potential water loss fractions used:

- 1. $\Sigma(T/T_p)$
- 2. $\Sigma(T/ET_p)$
- 3. $\Sigma(ET/ET_p)$
- 4. $(\Sigma T)/(\Sigma T_p)$
- 5. $(\Sigma T)/(\Sigma ET_p)$
- 6. $(\Sigma ET)/(\Sigma ET_p)$

Where: T = Actual transpiration (mm/day)
 T_p = Potential transpiration (mm/day)
 ET = Actual evapotranspiration (mm/day)
 ET_p = Potential evapotranspiration (mm/day)

All values are daily values. All summations are for a given phenological stage.

observed versus predicted data points was used to evaluate the suitability of each model formulation.

The simple additive regression model of the form:

$$\text{Yield} = \text{Constant}_0 + C_1(X1/X1') + C_2(X2/X2') + C_3(X3/X3') \quad [3]$$

where Xi/Xi' is one of the six ET relationships in table 2, gave first order results with formulations #1 and #2 ($R^2 \leq .4$). However, this formulation, though statistically sound, did not seem reasonable in the physical sense. It is not reasonable to assume that with complete deficits in stages two and three, a grain yield could still be achieved. This model was abandoned in favor of the more reasonable Hanks/Jensen form.

By using a logarithmic transform:

$$\text{Log}(Y) = (\text{Constant}_0) + \lambda_1 \text{Log}(X1/X1') + \lambda_2 \text{Log}(X2/X2') + \lambda_3 \text{Log}(X3/X3') \quad [4]$$

with a simple multiple regression routine, the gamma values for each stage of the Hanks/Jensen equation can be determined statistically with Y_p for that set of data statistically lumped into the leading constant C_0 .

Utilizing this technique, each of the ET relationships in Table 2 were evaluated in the Jensen/Hanks grain equation. ET relationship #4, which is the same as Hanks (1974) and Hill et al. (1974) used for corn and Rasmussen (1976) used for spring wheat, gave poor results ($R^2 \leq 0.2$). Initial inspection of the data revealed that for most of the data, water stress did not occur in the test sites (most were in Eastern Kansas). Therefore, yield differences could not be accounted for.

Further modelling using ET relationships #1 and #2 gave much better results ($R^2 \approx 0.4$ to 0.6). Number 2 gave the best overall results throughout the entire data set with the following equation showing the highest statistical significance ($R^2 \approx 0.6$):

Yield (bu/acre) =

$$2.856 (\Sigma(T/PET))_a^{.172} (\Sigma(T/PET))_b^{.104} (\Sigma(T/PET))_c^{.646} \quad [5]$$

Where a=growth stage from emergence to jointing

b=growth stage from jointing to heading

c=growth stage from heading to soft-dough

The observed versus predicted yield data are plotted in Figure 1.

The 1974-75 data covers a broad range of yields and the correlation is high (.80). The 1975-76 data set showed extreme variations within samples. Correlation with this data and modeled response is low (.56). The pooled correlation is 0.73 or an R^2 of 0.54.

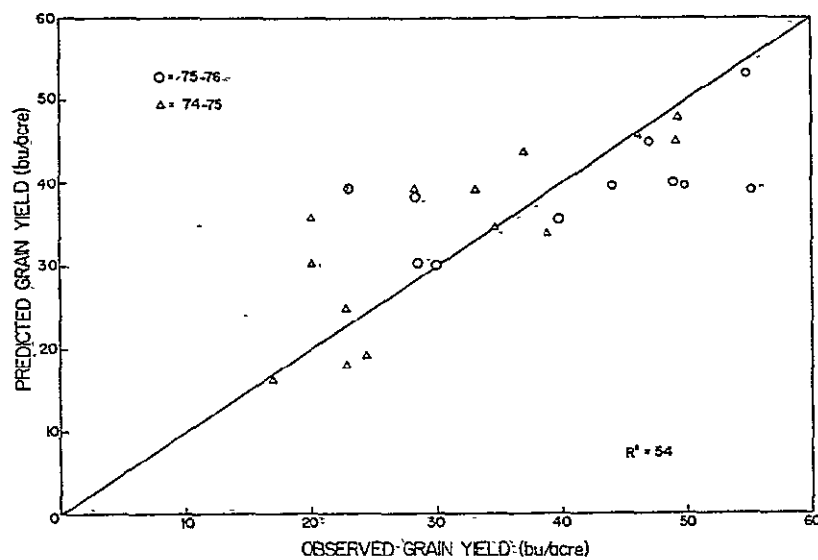


Fig. 1. Observed versus predicted 1:1 scatter diagram of calibration data set.

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MODEL EVALUATION

Additional yield data was obtained for the crop year 1976-1977 for sites across Kansas. In addition, a data set was obtained from Bushland, Texas in which the required LAI and soil moisture parameters were available. The Kansas data included data from an intensive experiment in which CCC (a plant growth regulant) was applied to three varieties to induce variate leaf area and water use conditions. Considering the wide variation of annual rainfall across Kansas and the variate conditions induced with CCC, a diverse set of test conditions was imposed.

A summary of these yield data as compared with modeled yields is given in Table 3, and plotted in Fig. 2. The pooled Pearson-moment coefficient is 0.81.

Additional attempts were made to modify the model by inclusion of temperature and potential yield terms; however, no significant increase in Pearson-moment was obtained when using the entire data set.

Table 3. Summary of observed versus predicted yields for all years.

KS 1975			KS 1976			KS 1977			BUSHLAND, TX		
<u>OBS</u>	<u>PRE</u>	<u>OBS/PRE</u>	<u>OBS</u>	<u>PRE</u>	<u>OBS/PRE</u>	<u>OBS</u>	<u>PRE</u>	<u>OBS/PRE</u>	<u>OBS</u>	<u>PRE</u>	<u>OBS/PRE</u>
-	45	-	30	31	.968	34	32	1.063	55	46	1.196
29	38	.763	44	40	1.100	30	29	1.034	40	40	1.000
20	35	.571	40	36	1.111	30	30	1.000	50	43	1.163
32	40	.800	50	39	1.282	25	25	1.000	45	44	1.023
49	47	1.043	55	52	1.058	21	30	.700	40	42	.952
49	45	1.089	47	45	1.044	24	26	.923	40	41	.976
37	44	.841	29	37	.784	30	26	1.154	45	41	1.098
34	34	1.000	-	40	-	27	26	1.038	20	22	.909
46	46	1.000	-	47	-	27	25	1.080	13	21	.619
24	25	.960	55	36	1.528	26	29	.897	35	38	.921
20	30	.667	29	31	.935	30	26	1.154	29	30	.967
39	34	1.147	49	40	1.225	18	26	.692	42	44	.955
25	19	1.316	23	39	.590	19	31	.613			
17	16	1.063				48	33	1.450			
24	17	1.412				54	44	1.230			
						27	34	.794			
						40	38	1.053			
						26	33	.788			
						38	28	1.357			
						37	36	1.028			

Pooled Corr. Coeff. = .81

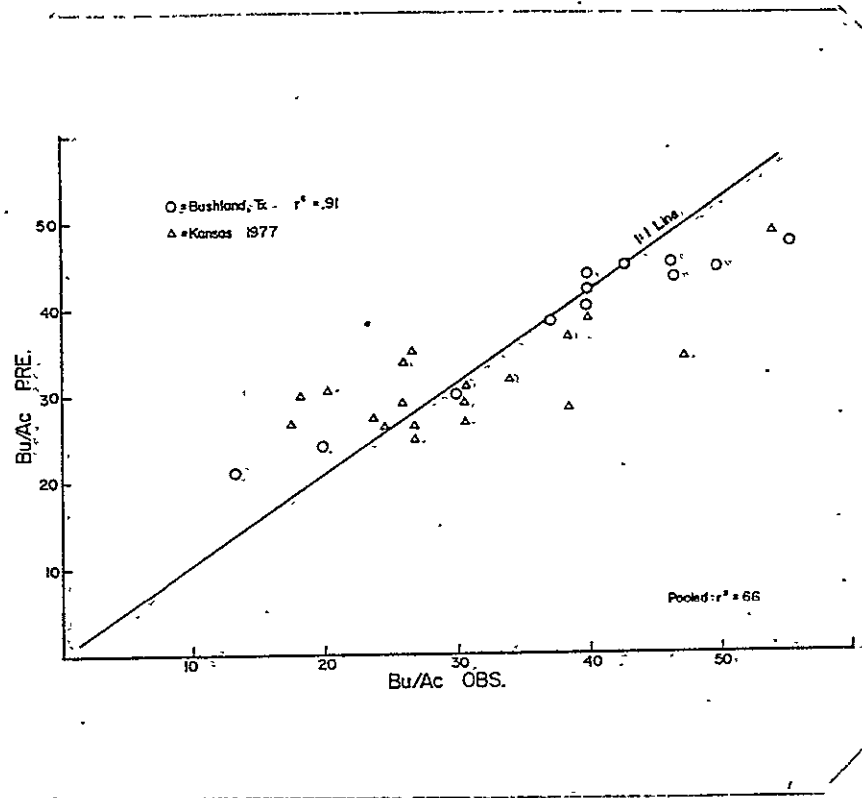


Fig. 2. Observed versus predicted 1:1 scatter diagram of test data set.

DISCUSSION

Emphasis was made at the beginning of this paper on the need for an operational yield modeling system for winter wheat in Kansas and other areas of the world. We believe that the model discussed here will provide first order results under conditions where water is the major limiting growth factor. No attempt is made in this model to consider the effects of fertilizer management problems, tillage practices, etc. However, considering the fact that yields can be modeled with reasonable accuracy across the entire state of Kansas and in Texas, we would again propose that water limits yield to a considerable extent in these areas. It is evident from this study that has been performed that other factors than those controlled by model inputs (temperature, radiation, rainfall, soil water characteristics, etc.) need to be accounted for in future modeling endeavors.

Considerable stress was placed upon the fact that T/T_p relationships should be the major indicator of water stress. The model formulation that gave the greatest degree of accuracy was the T/ET_p form. There are several reasons for the statistical suitability of this term. Water was not limiting to any extent in all data sets from Ellsworth and Riley counties. However, we were modeling winter wheat which has a long period of dormancy in the winter. According to the model T/T_p would approach one for this entire period (even though T_p is near zero). However, if T/ET_p is used, this number remains low -- being an indicator of little growth or photosynthesis.

The summation form is used (#1 and #2) instead of the fractional form (#4 and #5), due to increased statistical credibility because a summation form allows a given period's contribution to yield to be larger as time within the growth period is lengthened. Thus, if cool nights produce a

longer grain filling period in Western Kansas (as they often do), yield is allowed to increase. The fallibility of this approach lies in its physical meaning -- that yield could approach infinity if grain filling were prolonged to infinity. Evidence suggests that there is a genetically determined upper limit of phenological periods.

In reality then, the present model [5] integrates a number of components of yield into one equation: rate of growth (as indicated by T/ET_p), length of phenological period (cumulative photosynthesis), and water stress. Further refinements are currently being investigated. The individual components are best defined if isolated -- not lumped, as in the present model; however, the model can predict yields well within the range of field variability and should provide reasonable yield estimates where water is limiting.

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APPENDIX A

ALGORITHM FOR DAILY GROWTH MODEL FOR WINTER WHEAT

INPUT CARD5-

1. TITLE CARD. APPEARS AT THE TOP OF EACH OUTPUT PAGE. 80 COLUMNS OF INFORMATION.
2. CROP DATA. DATE SPECIFIED AS OCT 4, 1974 IN FIELD OF 32, LOCATICA, IN FIELD OF 32. (2 SEPARATE CARDS). (4A4).
3. VARIABLE FORMAT. SPECIFIES FORMAT OF INPUT FOR MODEL. INPUT CARD #7.
4. PARAMETERS FOR RUN. FIELDS OF 5F10.0,6F5.0.
5. THE MONTH DAY AND YEAR OF START OF DATA. SPECIFIED AS 02/14/75. (I2,I1,I2,I2)
6. THE LAST MONTH OF DATA SPECIFIED. I2.
7. CFLAG FOR SCRGHUM=1; SOYBEAN=2; WHEAT=3; CORN=4. (I2).
8. THETA VALUES FOR EACH LAYER. THETA MAX VALUES FOR EACH LAYER. THETA MIN VALUES FOR EACH LAYER. (15F5.0)
9. CHECK FOR BMTS SUBROUTINE. 01 IF NO, 02 IF YES. CHECK FOR IRRIGATION. 00 IF NO, # OF DAYS + 1 IF YES.
10. STAGEA DAYS FROM EMERGENCE. STAGEB DAYS FROM EMERGENCE. E.G. 34 59 FORMAT(I3,I1,I3).
11. COEFFICIENTS USED IN BIO METEOROLOGICAL TIME SCALE (SUBROUTINE (CLOCKER)). 6 CARDS. FOR WHEAT ONLY.
12. THE MONTH AND DAY OF PLANTING. FOR WHEAT ONLY. (I2,I1,I2)
13. DATA CARDS: DAILY SR,MAXT,MINT,LAI,RAIN,DL SHOULD CORRESPOND TO VARIABLE FORMAT #3 ABOVE. DL FOR WHEAT ONLY.

DECLARATION OF VARIABLES

```

      REAL *XHZC,MAXT,MINT,LAI,THEVAL(5),TVAL(5),ZVAL(5)/50.,250.,
      *Z300.,900./,CYAL(5),TTEMPX(5),THEMIN(5),KVAL2(5)/.05,.25,.25,
      *.25,.2/.KVAL1(5)/.1,.5,.4,2*0./,THETT,TAU,
      *RAINQL,RAINEM,TACC,MULT,TDAY,TX,TN,DL,
      *PFLDCF,KS,T,ET,FLOCF,T2,CV,
      *PTACC1
      REAL LB(7)/PT '-', 'EM -', 'JT -', 'HT -', 'HO -', 'SD -', 'RP->' /,
      *UB(7)/'EM', 'JT', 'BT', 'HT', 'HO', 'SD', 'RP', ' ' /, T3
      REAL KAY(6)/1.0,2.8,2.7,3.0,4.0,5.0/,DIFF,BTSTL(7,13)/91*0.0/,
      *TOTL(6)/6*0./,BTOTL(13)/13*0.0/
      INTEGER SYR(6),SPC(6),SDAY(6),SCLK(6),CLGCK,BTFLG,ICOUNT,RFLG,YEAR
      REAL LVAL(5)/50.,250.,2*300.,600./,MCNTL(12,14)
      REAL INTL,GRGSPH,CRESP,NRESP,NCE,OMTR,DM,CDM,TRESP,DLA1
      INTEGER CAY,YR,SCYSCR,CAL(12)/31,28,31,30,31,30,31,31,30,31,30,31
      */.TITLE(20),FLAG,CC(5)/5*0/,DAYT,PLANT(8),LOC(10),
      *K,PDAY,PMC,8MT,8FLAG,CTR,J,DT,N,8MS

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REAL PLAI,LAIMAX,TED,ETEC
INTEGER FLAGL,START
INTEGER SGSA,SGSB
INTEGER IPC(30),IDAY(30),IYR(30),IRRCHK,II
REAL IRR(30),FALLRT,FNTEMP
INTEGER IFLAG
REAL IRRIG
DIMENSION COEF(6,8)
REAL*8 FRMT(10)

C
C      INITIALIZE
C
  II=1
  RAINCL=0.0
  EST=0.0
  ET=0.0
  CCUNT=2.0
  CAYT=0
  TACC=0.0
  K=1.
  KS=1.0
  BMT=0.0
  T2=0.0
  TAU=0.0
  CV=3.0
  CT=60.
  FTACC1=0.0
  BTFLG=0
  RFLG=0
  CLOCK=0
  ICOUNT=0
  FNTEMP=15.0
  DO 204 J=1,6
    SYR(J)=0
    SHC(J)=0
    SDAY(J)=0
204 SCLK(J)=0
    START=0
    INTL=0.0
    GROSSP=0.0
    CRESP=0.0
    NRESP=C.0
    TRESP=0.0
    AGE=0.0
    CMTR=0.0
    CM=0.0
    CDM=0.0
    FLAI=0.0
    FLAGL=0
    LAIMAX=1.0
    FTMIN=15.0
    DO 202 J=1,12
      DO 203 I=1,14
203 MCNTL(J,I)=0.0
202 CCNTINUE
      DO 210 J=1,7
        DO 211 I=1,5
211 BTSTL(J,I)=0.0
210 CCNTINUE
C

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C          READ IN INPUT
C          CUT.PUT HEADINGS.
C
      READ (5,100,END=999) TITLE
      READ(5,100) PLANT
      READ(5,100) LCC
      READ(5,101) FRMT
      READ (5,102) PXH2G,TV,TIN,TS,U,ALPHA,FALLRT,CNST,X5,FLDCP,MULT
      T-ETT=TIN
      MFLDCP=FLCCP*1500.
      WRITE (6,103) TITLE
      WRITE (6,104) PXH2G,TV,TIN,TS,U,ALPHA,FALLRT,CNST,X5,MFLDCP,MULT
      WRITE(6,105) PLANT
      WRITE(6,106) LCC
      TI=TIN
      READ (5,107) MO,DAY,YR
      YEAR=YR
      KDAY=CAY
      READ (5,107) KMO
      IF(KMC-LT,MO) KMO=KMO+12
      MMQ=MO
      MMN=MO
      READ(5,107) SOYSOR
      ALPHAV=1.44
      GO TO (301,302,303,304),SOYSOR.
302- ALPHAV=1.71
      GO TO 301
303 ALPHAV=1.56
      CV=1.35
      DT=189.
      GO TO 301
304 ALPHAV=1.74
301 READ(5,108) THEVAL,THEMAX,THEMIN
      DO 200 I=1,5
200 CVAL(I)=(THEMAX(I)*.3)+(THEMIN(I)*.7)
      READ (5,107) 8FLAG,IRRCHK
      IF(SCYSCR.NE.1) GC TC 501
      READ(5,121) SGSA,SGSB
501 IF (8FLAG-2) 305,306,305
306 READ(5,109) (CCEF(I,J),J=1,8),I=1,6)
      READ (5,107) PMO,POAY
305 IF(IRRCHK.EQ.0) GC TC 359
      READ(5,120) (MC(I),ICAY(I),IYR(I),IRR(I),I=1,IRRCHK)
      J=IRRCHK-1
      WRITE(6,122)
      WRITE(6,123) (IMG(I),IDAY(I),IYR(I),IRR(I),I=1,J)
359 FLAG=0
      IF (TS-GE,X5) FLAG=1
C
C          TOP OF LCCP OF ANALYSIS.
C
206 WRITE (6,103) TITLE
      WRITE(6,110)
      LIM=CAL(MMC)
      IF(MMC.EQ.2.AND.MOD((YR+1),4).EQ.0) LIM=25
      DO 207 JJJ=KDAY,LIM
      IF(MMC.EQ.1.AND.JJJ.EQ.1) YEAR=YEAR+1
C
      IF(SCYSCR.EQ.1) GC TC 308
      GO TO (307,308),8FLAG

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308 READ(5,FRMT,END=332) SR,MAXT,MINT,LAI,RAIN,DL
GO TO 309
307 READ(5,FRMT,END=332) SR,MAXT,MINT,LAI,RAIN
309 COVER=LAI/CV
IF(COVER.GT.0.0) DAYT=CAXT+1
IF(COVER.GT.1.0) CCVER=1.00
IF(DAYT-0.1) 333,333,310
310 IF(CCVER.LT..4) COVER=.4
C
C      IF TEMPERATURE IS IN DEGREES F.
C      PLACE CONVERSIONS T=(T-32.0)*5./9. FOR
C      MIN AND MAX HERE.
C
333 MAXT=(MAXT-32.0)*5./9.
MINT=(MINT-32.0)*5./9.
IFLAG=0
IF(IRRCHK.EQ.0) GO TO 361
IF((IMOD(II).EQ.MMO.AND.IDAY(II).EQ.JJJ).AND.IYR(II).EQ.YEAR)
*GO TO 363
GO TO 361
363 RAIN=RAIN+IRR(II)
IFLAG=1
IRRIG=IRR(II)*10.
II=II+1
361 RAIN=RAIN*10.0
RAINEW=RAIN+RAINCL
RAINOL=RAIN
IF(RAINEW.LT.6.0) GO TO 311
FLAG=0
EST=0.0
COUNT=2.0
311 TMP=(3*MAXT+MINT)/4.0
SSD=DELTA(TMP)
313 GO TO (312,315),8FLAG
315 IF(MMO.EQ.PMO.AND.JJJ.EQ.PDAY) BMT=1
IF(BMT-1) 312,316,312
C
C      FOR WHEAT ONLY.
C
316 TX=MAXT
TN=MINT
C
C      *****
C      CALL BIO-METEOLOGICAL TIME SCALE SUBROUTINE:
C
CALL CLOKER(CGEF,TN,TX,CL,TCAY,K,MULT,TACC,CLOCK,MMO,JJJ,YEAR,
*      BTFEG,DIFF,SYR,SHO,SDAY,SCLK,ICOUNT,RFEG,KAY,
*      PTACC1)
C
C      *****
C
C      CALL CF SUBROUTINE TO CALCULATE POT EVAP.
C
312 CALL PCTEVA(EAT,SOYSOR,RN,SR,ALPHA,SSD,EO,DAYT)
C
C      *****
C
TI=TI-ET+RAIN
IF(TI.GE.PFLDCP) TI=PFLDCP
C
C      IF POT EVAP IS . ZERO ALL EVAP ARE ZERO

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C      IF (EC.GT.0.0) GO TO 317
      ED=0.0
      ES=0.0
      T =0.0
      T2=0.0
      A=0.0
      GO TO 325
C      *****
C      CALL TRANSPIRATION SUBROUTINE
C
C 317 CALL TRANS(T1,MXH2G,TV,KS,LAI,T,ALPHA,RN,SSD,COVER,TAU,ALPHAV,
      *DRY,SCYSOR,T2,TGDD,TACC,FALLRT)
C      *****
C
C      CALL SCIL EVAPORATION SUBROUTINE.
C      CALL EVAP(FLAG,LAI,RN,EST,ES,U,CNST,COUNT,SSD,DRY,COVER,DAYT,TAU,
      *SOYSOR)
C      *****
C      CALCULATION OF A EVAPORATION
C
C      GO TO (319,320,321,319),SOYSOR
C
C      FOR SOYBEAN
C
C 320 IF (MAXT-31.) 322,318,318
C
C      FOR WHEAT
C
C 321 IF (MAXT-27.) 322,323,323
C
C      FOR SORGHUM OR CERN
C
C 319 IF(MAXT.GE.33.0) GO TO 323
C 322 A=0.0
C      GO TO 324
C 318 A=-.25*T
C      GO TO 324
C 323 A=-.1*T
C 324 IF(MAXT.GE.-3.0) GO TO 325
C      ES=0.0
C      A=0.0
C 325 IF(KS.LT.1.0) A=0.0
C      T2=T2+A
C      TAVAIL=THETT-(TV*1500)
C      KS=TAVAIL/((FALLRT*MXH2C)
C      IF (KS.GT.1) KS=1
C      IF (KS.LT.0.0) KS=0.0
C      T3=T2*KS
C      ET=T3+ES
C      *****
C      CALL DISTR(T3,TVAL,KVAL1,KVAL2,LAI)
C      *****
C      RUNOFF=0.0
C      DRAIN=0.0
C      CALL CAY1 (THEVAL,ZVAL,DRAIN,CD,THEMAX),
C      IF (RAIN.EQ.0.)GO TO 401
C      *****

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      IF (IFLAG.EQ.1) GO TO 366
      GO TO 367
366  RAIN=RAIN-IRRIG
      CALL CAYC (THEVAL,RAIN,ZVAL,RUNOFF,CD,THEMAX)
      CALL CAY2 (THEVAL,IRRIG,ZVAL,RUNOFF,CD,THEMAX)
      RAIN=RAIN+IRRIG
      GO TO 401
367  CALL CAYO (THEVAL,RAIN,ZVAL,RUNOFF,CD,THEMAX)
C      *****
C      *****
401  CALL MCIST (THEVAL,ES,TVAL,ZVAL,THEMIN)
C      *****
      IF (EQ.AE.0.0) GO TO 405
      TEO=0.0
      ETEO=C.0
      GO TO 406
405  TEC=T3/EG
      ETEO=ET/EC
406  THETT=0
      DO 201 J=1,5
201  THETT=(THEVAL(J)*LVAL(J))+THETT
      GO TO (407,402,403,1000),SGYSOR
402  CALL JIN(LAI,PLAI,INTL,GRCSPH,TRESP,NCE,DM,CDM,SR,START,KS)
      GO TO 404
403  DLAI=LAI+.025.
      IF (DLAI.GT.4.62) DLAI=4.62
      INTL=5.21*SR*DLAI**.3296
C
C      TCM'S PROGRAM
      CALL TCM (FLAGL,LAI,PLAI,K,TACC,GRCSPH,SR,MAXT,DRESP,CDM,
      *DL,NRESP,NCE,DM,MINT,PTMIN,LAIMAX,KS)
C
      TRESP=CRESP+NRESP
      GO TO 404
407  CALL SCRGPH (CAYT,MAXT,MINT,PTMIN,SGSA,SGSB,INTL,SR,LAI,GRCSPH,
      *DRESP,CL,CDM,NCE,NRESP,DM,PLAI,LAIMAX,FLAGL,PNTMP,KS)
      TRESP=CRESP+NRESP
404  IF (T3.EQ.0.0) GO TO 335
      DMTR=CM/T3
      GO TO 336
335  DMTR=C.0
336  PTMIN=MINT
      FLAI=LAI
C
C      PRINTOUT DAILY VALUES
      WRITE (6,11)MMO,JJJ,SR,MAXT,MINT,RAIN,LAI,T3,EG,ET,INTL,
      *GRCSPH,CRESP,NRESP,TRESP,NCE,DMTR,DM,CDM,TACC,THETT,KS
C
      MCNTL(MMO,1)=MCNTL(MMO,1)+SR
      MCNTL(MMO,2)=MCNTL(MMO,2)+RAIN
      MCNTL(MMO,3)=MCNTL(MMO,3)+T3
      MCNTL(MMO,4)=MCNTL(MMO,4)+EG
      MCNTL(MMO,5)=MCNTL(MMO,5)+ET
      MCNTL(MMO,6)=MCNTL(MMO,6)+INTL
      MCNTL(MMO,7)=MCNTL(MMO,7)+GRCSPH
      MCNTL(MMO,8)=MCNTL(MMO,8)+DRESP
      MCNTL(MMO,9)=MCNTL(MMO,9)+NRESP
      MCNTL(MMO,10)=MCNTL(MMO,10)+TRESP
      MCNTL(MMO,11)=MCNTL(MMO,11)+NCE
      MCNTL(MMO,12)=MCNTL(MMO,12)+DMTR

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      MCNTL(MMO,13)=PCNTL(MMC,13)+CM
      MCNTL(MMC,14)=CDM
      BMS=K
      IF (RFLG.EC.1) BMS=BMS+1
      BTSTL(BMS,1)=BTSTL(BMS,1)+GRCSPPH
      BTSTL(BMS,2)=BTSTL(BMS,2)+TRESP
      BTSTL(BMS,3)=BTSTL(BMS,3)+NCE
      BTSTL(BMS,4)=BTSTL(BMS,4)+DMTR
      BTSTL(BMS,5)=CCM
      BTSTL(BMS,6)=BTSTL(BMS,6)+T3
      BTSTL(BMS,7)=BTSTL(BMS,7)+ET
      BTSTL(BMS,8)=BTSTL(BMS,8)+TEO
      BTSTL(BMS,9)=BTSTL(BMS,9)+ETEG
      BTSTL(BMS,10)=BTSTL(BMS,10)+KS
      BTSTL(BMS,11)=BTSTL(BMS,11)+T2
      BTSTL(BMS,12)=BTSTL(BMS,12)+SR
      BTSTL(BMS,13)=BTSTL(BMS,13)+INTL
207 CONTINUE
C
332 WRITE(6,112) (MCNTL(MMO,J),J=1,13)
C
      MMC=MMC+1
      IF (MMC.GT.12) MMC=MMC-12
      KDAY=1
      IF (MMF.EC.KMO) GO TO 999
      MMF=MMF+1
      GO TO 206
999 WRITE(6,103) TITLE
      WRITE(6,113)
      MMQ=MC
      DO 212 MMF=MC,KMC
      WRITE(6,114) MMC,MCNTL(MMO,2),MONTL(MMC,5),MCNTL(MMC,7),
      *PCNTL(MMC,10),MONTL(MMC,11),MGNTL(MMO,12),MONTL(MMO,14)
      TOTL(1)=TCTL(1)+PCNTL(MMC,2)
      TOTL(2)=TOTL(2)+PCNTL(MMC,5)
      TOTL(3)=TOTL(3)+PCNTL(MMC,7)
      TOTL(4)=TOTL(4)+PCNTL(MMC,10)
      TOTL(5)=TOTL(5)+MONTL(MMO,11)
      TOTL(6)=TOTL(6)+PCNTL(MMC,12)
      MMQ=MMQ+1
      IF (MMC.GT.12) MMQ=1
212 CONTINUE
      WRITE(6,115) (TCTL(J),J=1,6)
      IF (BFLAG-2) 1000,998,1000
998 WRITE(6,116)
      DO 213 J=1,BMS
      WRITE(6,117) LB(J),UB(J),(BTSTL(J,M),M=1,13)
      CO 214 M=1,13
214 BTCTL(M)=BTOTL(M)+BTSTL(J,M)
213 CCNTINUE
      WRITE(6,118) (BTCTL(M),M=1,4),(BTOTL(M),M=6,13)
      WRITE(6,119) (KAY(J),SCLK(J),SMO(J),SDAY(J),SYR(J),J=1,K)
100 FORMAT (20A4)
101 FORMAT (10A8)
102 FORMAT (5F10.0,6F5.0)
103 FORMAT ('1',20X,20A4,///)
104 FORMAT ('0',19X,'MAXIMUM AVAILABLE WATER (MM).....',
      * F10.4,///,20X,'THETA SUB V (15 BAR).....',
      * F10.4,///,20X,'THETA INITIAL IN 5 FT. PROFILE (MM).....',
      * F10.4,///,20X,'THETA SUB 5 CM. LAYER.....')

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*NRESP,DM,PLAI,LAIMAX,KS
REAL CTEMP,NTEMP,LM,TSTR,PNTMP,LMLAI
INTEGER SGSA,SGSB,CAYT,FLAGL
CTEMP=(2*MAXT+PTMIN)/3
NTEMP=(MAXT+2*MINT)/3
LMLAI=LA I
IF(LMLAI.GT.6.65) LMLAI=6.65
IF(DAYT.EQ.0) GC TC 59
LM=1.0
IF(DAYT.LT.SGSA) GC TO 10
IF(FLAGL.EQ.1) GC TO 12
IF(LAI.LT.PLAI) GO TO 13
GO TO 14
13 LAIMAX=PLAI
FLAGL=1
12 LM=.75+.25*(LAI/LAIMAX)
14 IF(DAYT.LT.SGSB) GO TO 20
INTL=.1065*SR*(77.08+1.69*LMLAI)
GROSPH=2000*(1-EXP(-.0000895*INTL))*KS
GO TO 30
20 INTL=.1065*SR*38.436*LMLAI**.486
GROSPH=2000*(1-EXP(-.0000895*INTL))*KS
GO TO 30
10 INTL=.1065*SR*38.436*LMLAI**.486
GROSPH=2000*(1-EXP(-.000059*INTL))*KS
30 IF(MAXT.GT.33.) GC TC 16
GO TO 17
16 IF(MAXT.NE.MINT) GO TO 11
TSTR=0.0
GO TO 15
11 TSTR=(MAXT-33)/((MAXT-.5*MINT-.5*PTMIN))
15 GROSPH=GROSPH*(1-TSTR)
17 DRESP=CL*(.011667*GROSPH+LM*CDM*(.002955+.000128*OTEMP+.000067
* OTEMP**2))*(-1)
NRESP=(24-DL)*(0.11667*(GROSPH+DRESP)+LM*CDM*(.002955+.000128*
* NTEMP+.000067*NTEMP**2))*(-1)
NCE=GROSPH+DRESP+NRESP
DM=.0067*NCE
CDM=CDM+DM
59 PNTMP=NTEMP
RETURN
END
SUBROUTINE TCM(FLAGL,LAI,PLAI,K,TACC,GROSPH,SR,MAXT,DRESP,CDM,
*CL,NRESP,NCE,DM,MINT,PTMIN,LAIMAX,KS)
REAL LAI,PLAI,TACC,GROSPH,SR,MAXT,DRESP,CDM,CL,NRESP,NCE,DM,MINT,
*CTEMP,NTEMP,LAIMAX,PTMIN,LAI,KS
REAL TC,TN,TSTR,TSTR1,TSTR2
INTEGER FLAGL,K
CTEMP=(2*MAXT+PTMIN+3*273.15)/3
NTEMP=(MAXT+2*PTMIN+3*273.15)/3
IF(MAXT.GT.23.) GC TC 20
TO=23.
TSTR1=1.
GO TO 21
20 TN=(PTMIN+MINT)/2
IF (TN .GT. 23) TN = 23
TO=MAXT
IF(TN.LT.5.) TN=5.
TSTR1=1-(MAXT-23.)/(MAXT-TN)
21 IF(PTMIN.LT.5.) GO TC 22

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* F10.4///,20X,'U (MM).....'
* F10.4///,20X,'ALPHA (P-T).....'
* F10.4///,20X,'FALLRT.....'
* F10.4///,20X,'SOIL CONSTANT (MM DAY TO -1/2).....'
* F10.4///,20X,'X SUB 5 (INIT.WATER CONTENT IN 5 CM. LAYER,WT.).....'
* F10.4///,20X,'FIELD CAPACITY.....'
* F10.4///,20X,'BMTS MULTIPLIER.....'
* F10.4)
105 FORMAT('O',19X,'PLANTING DATE.....',
*'..'.20A4)
106 FORMAT('O',19X,'FIELD/LOCATCN.....',
*'..'.20A4)
107 FORMAT(I2,I,X,I2,I,X,I2)
108 FORMAT(15F5.0)
109 FORMAT(8E10.4)
110 FORMAT(' ',33X,'TRAN PGT. TOT. INT. GROSS DAY NIGHT ',
*'TOT.',21X,'CUM',/, ' MC DAY SR MXT MNT RAIN LAI EVAP EVAP',
*' EVAP LIGHT PHCTC RESP RESP RESP NCE DM/TR OM ',
*'DM BMTS THETA KS',/, ' (LYS) (C) (C) (MM) (MM)',
*' (MM) (MM) PE/CNCF-----MG/(CM**2)/DAY)J-----',
*' (MG/(CM**2)) (MM)',/)
111 FORMAT(' ',I2,I3,F6.0,F5.0,F5.0,F5.1,F5.2,F6.2,F6.2,F7.0,
*F7.1,F7.1,F7.1,F7.1,F7.1,F6.1,F6.1,F6.1,F5.2,F7.1,F6.2)
112 FORMAT('TOTOT.',F7.0,11X,F4.0,7X,F4.0,F6.0,F5.0,F8.0,F7.0,F7.0,
*F7.0,F7.0,F7.0,F6.0,F6.0)
113 FORMAT(/,,1X,18X,'TCTIAL GRCS$',36X,'CUP',/,1X,10X,
*'RAIN EVAP PHQTC TCT.RESP ACE DM/TRAN DM',
*/,1X,' MCNTH (MM) ',',',****('MG/(CM**2)/DAY')****',
*12X,'(MG/(CM**2))',/,+',',.77(' '),/)
114 FORMAT(' ',14,5X,F5.1,4X,F5.1,2X,F7.1,6X,F7.1,1X,F7.1,4X,F5.1,
*3X,F6.1)
115 FORMAT('O', ' TOT.',4X,F4.0,4X,F5.0,3X,F6.0,6X,F7.0,2X,
*F6.0,4X,F5.0)
116 FORMAT(/,, ' -.11X,'GRCSS',31X,'CUM TRAN TOT. RATIO',
*' RATIO RATIO POT.',15X,'INT.',/, ' ',11X,'PHOTO TOT.',
*'RESP NCE DM/TRAN OM EVAP(2) EVAP(2) T3/E0(2) ',
*'ET/EC(2) T3/T2(2) TRAN(2) SR LIGHT',/, ' ', ' BMTS ',
*'*PG/(CM**2)/DAY')***',9X,'(MG/(CM**2))',51X,'(LYS) ',
*'(PE/CNCF)',/,+',',.123(' '),/)
117 FORMAT(' ',A4,A2,F10.1,F9.1,F9.1,F9.1,F8.1,F10.2,F8.2,F9.2,
*F9.2,F9.2,F8.2,F9.0,F10.0)
118 FORMAT('O', ' TCT.',F10.0,F9.0,F9.0,F9.0,9X,F9.0,F8.0,F9.0,
*F9.0,F9.0,F8.0,F9.0,F10.0)
119 FORMAT(/,, ' EMERGENCE DATE (BMTS=',F4.2,' DAYS=',13,')...'.12,
*/',.12,/',.12,/, ' JOINTING DATE (BMTS=',F4.2,' DAYS=',13,')...'.12,
*/',.12,/',.12,/, ' BOILING DATE (BMTS=',F4.2,' DAYS=',13,
*)....'.12,/',.12,/',.12,/, ' HEADING DATE (BMTS=',F4.2,' DAYS=',
*13,')....'.12,/',.12,/',.12,/, ' SOFT DOUGH DATE (BMTS=',F4.2,
*' DAYS=',13,').12,/',.12,/',.12,/, ' RIPE DATE (BMTS=',F4.2,
*' DAYS=',13,')....'.12,/',.12,/',.12,/',.12,/',.12,/'
120 FCFORMAT(8(12,F4.2))
121 FORMAT(I3,I,X,I3)
122 FORMAT(/,, ' ',19X,'IRRIGATION DATA',,,,20X,' DATE ',12X,
* 'AMOUNT [CM]',/)
123 FORMAT(' ',19X,I2, '/',I2, '/',I2,16X,F5.2)
1000 RETURN
END
SUBROUTINE SORGRP(DAYT,MAXT,MINT,PTMIN,SGSA,SGSB,INTL,SR,LAI,
*GRCS$,DRESP,DL,CDM,NCE,NRESP,OM,PLAT,LAI,PAX,FLAGL,PNTPEM,K$)
REAL MAXT,MINT,PTMIN,INTL,SR,LAI,GRCS$,DRESP,DL,CDM,NCE,
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```

TSTR2=1.
GO TO 23
22 TSTR2=1-(5.-PTMIN)/(TD-PTMIN)
TSTR=TSTR1*TSTR2
23 ILAI=LAI
IF (FLAGL.EQ.1) GO TO 12
IF (K.GE.3.AND.LAI.LT.PLA1) GO TO 11
GO TO 12
11 LAIMAX=PLAI
FLAGL=1
12 GO TO (1,2,3,3,4,4),K
4 IF (LAI.GT.1.5) GO TO 13
ILAI=ILAI+.025
IF (TACC.GT.4.5) GO TO 14
GO TO 2
13 ILAI=ILAI+.025
3 IF (LAI.LE.1.5) GO TO 2
IF (ILAI.GT.4.62) ILAI=4.62
GROSPH=(1012-1012*EXP(-.0055*SR*.5739*ILAI**.3296))*KS*TSTR
GO TO 17
14 GROSPH=0.0
GO TO 16
2 IF (MAXT.LT.5.0) GO TO 16
GO TO 19
18 GROSPH=0.0
GO TO 17
19 IF (ILAI.GT.4.62) ILAI=4.62
GROSPH=(440-440*EXP(-.0025*SR*.5739*ILAI**.3296))*KS
* TSTR
17 IF (FLAGL.EQ.1) GO TO 16
DRESP=(-.27601-.014775*GROSPH-.002329*CDM*(1+.0035087*OTEMP+
* .0001*CTEMP**2))*OL
NRESP=(24-OL)*(-.27601-.014775*(GROSPH+DRESP)-.002329*CDM
* (1+.0035087*NTEMP+.0001*NTEMP**2))
GO TO 1
16 DRESP=(-.27601-.014775*GROSPH-.002329*CDM*(ILAI/LAIMAX)*
* (1+.0035087*CTEMP+.0001*OTEMP**2))*OL
NRESP=(24-OL)*(-.27601-.014775*(GROSPH+DRESP)-.002329*CDM*
* (ILAI/LAIMAX)*(1+.0035087*NTEMP+.0001*NTEMP**2))
1 NCE=GROSPH+DRESP+NRESP
OM=NCE*.C067
CDM=CCM+CM
RETURN
END
SUBROUTINE TRANS(TI,MXH2O,TV,KS,LAI,T,ALPHA,RN,SSD,COVER,TAU,
1ALPHAV,DRY,SGYSCR,T2,TCDC,TACC,FALLRT)

```

SUBROUTINE: CALCULATION OF TRANSPIRATION.

```

*****
REAL LAI,MXH2O,KS,T2,TGDE,TACC,FALLRT
INTEGER SCYSCR
TAVAIL=TI-(TV*1520.)
KS=TAVAIL/(FALLRT*MXH2O)
IF (KS.GT.1.) KS=1
IF (KS.LT.0.0) KS=0.0
GO TO (1,1,3,4),SGYSCR

```

FOR SORGHUM AND SOYBEAN

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```

1 TAU=EXP(-.398*LAI)
  IF (LAI-2.5) 53,51,51
C
C      FCR WHEAT
C
3 TAU=EXP(-.737*LAI)
  IF (TACC.GT.3.OR.LAI-GE.1.25) GO TO 30
  GO TO 50
30 IF (TACC.GT.4) GO TO 52
  GO TO 51
C
C      FCR CORN
C
4 DRY=LAI
  TAU=EXP(-.389*DRY+0.1438)
  IF (LAI.LE.38) TAU=1.
  IF (LAI-GE.2.5-OR.TGCC-GE.1400) GO TO 41
  GO TO 50
41 IF (LAI.LT.2.5-AND.TGCC-GE.2000) GO TO 50
  GO TO 51
C
C
50 T=KS*ALPHA*(1.0-TAU)*SSC*RN/58.3
  GO TO 59
51 T=KS*(ALPHA-TAU)*SSC*RN/58.3
  GO TO 59
52 T=KS*ALPHA*(1-(EXP(-.737*LAI)))*SSC*RN/58.3
  GO TO 59
53 T=KS*ALPHA*(1-(EXP(-.398*LAI)))*SSC*RN/58.3
C
C
99 IF (KS-EG.0.0) GO TO 98
  T2=T*I/KS
  GO TO 97
98 T2=0.0
97 RETURN
END
SUBROUTINE JIM(LAI,PLAI,INTL,GROSPH,TRESP,NCE,DM,CDM,SR,START,KS)
REAL LAI,SR,PLAI,INTL,GROSPH,TPESP,NCE,DM,CDM,KS
REAL PAR,PCTINT,ARG
INTEGER START
IF (LAI-EG.0.0) GO TO 99
START=1
PAR=11.3*SR
IF (LAI-GE.PLAI) GO TO 1
ARG=10*LAI
PCTINT=8.31*ALOG(ARG)+63.6
GO TO 10
1 IF (LAI.LE.2.7) GO TO 2
  IF (LAI.LE.5.2) GO TO 3
  PCTINT=95
  GO TO 10
2 PCTINT=32.5*LAI+.46
  GO TO 10
3 PCTINT=1.27*LAI+88.4
10 INTL=PAR*PCTINT*.01
  IF ((LAI-GE.PLAI-OR.LAI-GE.3.5).OR.INTL-GE.5150) GO TO 20
  GROSPH=(5.91E-17*INTL*.056)*KS
  GO TO 30
20 GROSPH=(.715*INTL*.728)*KS

```

```

30 TRESP=.26*GROSPH+4.455
   IF (TRESP.LT.0.0) TRESP=0.0
   NCE=GROSPH-TRESP
   DM=.007*NCE
   CDM=CDM+DM
   GO TO 100
99 IF (START.EQ.0) GO TO 100
   INTL=C.0
   GROSPH=0.0
   TRESP=0.0
   NCE=0.0
   CM=0.0
100 RETURN
   END
C
C *****
C   SUBROUTINE POT.EVA(LAI,CFLAG,RN,SR,ALPHA,SSD,EO,DAYT)
C
C   SUBROUTINE:  CALCULATION OF POT. EVAP.
C
C   *****
C   INTEGER CFLAG,DAYT
C   REAL LAI
C   IF (CFLAG-3) 5,6,7
5  IF (LAI.LT.3.0) GO TO 3
   IF (CFLAG-1) 1,1,2
C
C       FOR SORGHUM
C
C   1 RN=.8368*SR-130.78
C     GO TO 4
C
C       FOR SOYBEAN
C
C   2 RN=.8049*SR-135.97
C     GO TO 4
C   3 RN=.7248*SR-50.11
C     GO TO 4
C
C       FOR WHEAT
C
C   6 RN=.8678*SR-163.56
C     IF (DAYT.LE.168) RN=.9593*SR-213.10
C     IF (DAYT.GT.202) RN=.9258*SR-157.4208
C     GO TO 4
C
C       FOR CORN
C
C   7 IF (LAI.GE.3.0) GO TO 8
C     RN=.8608*SR-103.92
C     GO TO 4
C   8 RN=.846*SR-144.49
C     IF (DAYT.GT.84) RN=.766*SR-99.84
C   4 EO=ALPHA*SSD*RN/58.3
C     RETURN
C     END
C
C   *****
C   *****
C   SUBROUTINE EVAP(FLAG,LAI,RN,EST,ES,U,CNST,COUNT,SSD,DRY,COVER,
C   1 DAYT,TAU,SOYSOR)
C

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C          SUBROUTINE:  CALCULATION OF SOIL EVAP.
C
C          *****
C          REAL LA1,MRNS
C          INTEGER FLAG,DAYT,SCYSCR
C          GO TO (2,6,6,5),SCYSCR
C
C          FOR SCYBEAN AND WHEAT
C
C          6 IF (CCYER.GT.LA1) TAU=.852
C          GO TO 2
C
C          FOR CORN
C
C          5 TAU=EXP(-.389*ORY+G.1438)
C          IF (LA1.LE.0.38) TAU=1.0
C          IF (DAYT.GT.90.AND.LA1.LT.3.67) TAU=.270
C
C          SWITCH AS TO WHICH SOIL EVAPORATION FORMULA
C          TO USE
C
C          2 IF (FLAG-1) 1,3,3
C          1 ES=TAU*SSD*RN/58.3
C          EST=EST+ES
C          IF (EST.LE.U) GO TO 4
C          FLAG=2
C          ES=ES*0.6
C          GO TO 4
C          3 ES=CNST*(SORT(CCUNT)-SQRT(COUNT-1.0))
C          COUNT=CCUNT+1.0
C          4 MRNS=TAU*RN/58.3
C          IF (MRNS.LT.ES) ES=MRNS
C          RETURN
C          END
C
C          *****
C          FUNCTION DELTA(T)
C          *****
C          DELTA=0.0155416*T - 0.000005*T**3 + 0.0000001*T**4 + 0.40408273
C          RETURN
C          END
C
C          *****
C          SUBROUTINE  CLCKER
C
C          PURPOSE      CALCULATE PART OF BIO-TIME TODAY,BAIER MODEL
C
C          DESCRIPTION OF PARAMETERS
C          CCEF:        COEFFICIENT TO CALCULATE TIME
C          TN:          MIN TEMP
C          TX:          MAX TEMP
C          DL:          DAY LENGTH
C          TACC:        TOTAL OF TIME PARTS
C          TCAY:        TCAYS TIME PART
C          K:           INDEX INTO CCEF
C
C          SUBROUTINE CLOKER(COEF,TN,TX,DL,TDAY,K,MULT,TACC,CLOCK,MMO,JJJ,
C          *              YEAR,8TFLG,DIFF,SYR,SHC,SDAY,SCLK,ICOUNT,
C          *              RFLG,KAY,PTACC1)
C
C          *****
C          REAL CCEF(6,8),TN,TX,DL,TDAY,MULT,TACC,DIFF,KAY(6),PTACC1
C          INTEGER K,CLOCK,MMO,JJJ,YEAR,8TFLG,SYR(6),SMO(6),SDAY(6),SCLK(6),

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      *      ICCUNT,RFLG
C      TX=((9./5.)*TX)+32.
C      TN=((9./5.)*TN)+32.
C      FIND DAYLENGTH CONTRIBUTION TO BIO-TIME
C      V1=CCEF(K,2)*(DL-COEF(K,1))+COEF(K,3)*(DL-COEF(K,1))**2
C      IF(V1.LT.0.) V1=0.0
C      FIND MAX TEMP CONTRIBUTION TO BIO-TIME
C      V2=COEF(K,5)*(TX-COEF(K,4))+COEF(K,6)*(TX-COEF(K,4))**2
C      IF (V2.LT.0.0.CR.TX.LT.23.64) V2=0.0
C      FIND MIN TEMP CONTRIBUTION TO BIO-TIME
C      V3=COEF(K,7)*(TN-COEF(K,4))+COEF(K,8)*(TN-COEF(K,4))**2
C      IF(V3.LT.0.0) V3=0.0
C      TODAYS CONTRIBUTION TO BIO-TIME
C      TODAY=V1*(V2+V3)
C      CUMMALATIVE SUMS FOR BMTS
C      IF(K.EQ.3.OR.K.EQ.4) TCAY=TODAY*MULT
C      TACC=TACC+TCAY
C      CLCCK=CLCCK+1
C      IF((MPC.GT.9.AND.MMO.LE.12).AND.TACC.GT.1.6) TACC=1.6
C      IF(BTFLG.EQ.1) GC TO 10
C      IF(K.EQ.3.AND.TACC.GE.2.7) GC TO 20
C      GO TO 30
20. BTFLG=1
C      GO TO 99
30 DIFF=TACC-PTACC1
C      IF(SYR(2).EQ.0.AND.TACC.GE.2.8) GO TO 40
C      IF((TACC.GE.1.95.AND.TACC.LT.2.8).AND.K.NE.3.) GC TO 50
C      GO TO 10
50 IF(DIFF.GE..02) ICCUNT=ICOUNT+1
C      IF(ICCUNT.LT.10) GO TO 100
C      KAY(2)=TACC
40 TACC=2.00
C      GC TO 99
10 IF(RFLG.EQ.1) GC TO 111
C      IF(TACC.GE.KAY(K).AND.K.LT.6) GO TO 99
C      IF(TACC.LT.5.00) GC TO 100
C      RFLG=1
99 SYR(K)=YEAR
C      SMO(K)=MPC
C      SDAY(K)=JJJ
C      SCLK(K)=CLOCK
C      CLCCK=0
C      IF(K.LT.6) K=K+1
100 PTACC1=TACC
111 RETURN
C      END
C      .....
C      SUBROUTINE DAY1(THVAL,ZVAL,DRAIN,CD,THEMAX)

```



```

C
-C
C
C
      SUBROUTINE TO CALCULATE THE TRANSPIRATION IN EACH LAYER.
C
      *****
      DIMENSION TVAL(5),KVAL1(5),KVAL2(5)
      REAL KVAL1,KVAL2,LAI
      IF (LAI.GT.1) GO TO 3
      DO 2 I=1,5
2    TVAL(I)=T*KVAL1(I)
      GO TO 5
3    DO 4 I=1,5
4    TVAL(I)=T*KVAL2(I)
5    RETURN
      END
C
      *****
      SUBROUTINE MOIST (THEVAL,ES,TVAL,ZVAL,THEMIN)
C
C
C
C
      TC CALCULATE THE SOIL MOISTURE CONTENT IN EACH LAYER
C
      *****
      DIMENSION THEVAL(5),TVAL(5),ZVAL(5),THEMIN(5)
      REAL ELEFT1,ELEFT2,RMD,ES
      ELEFT1=ES
      IF (ELEFT1.EQ.0.0) GO TO 2.
1    DO 19 I=1,5
      IF (THEVAL(I).EQ..1) GO TO 19
      ELEFT2=ELEFT1/ZVAL(I)
      TCK=THEVAL(I)-ELEFT2
      IF (TCK.LT..1) GO TO 11
      THEVAL(I)=TCK
      GO TO 2
11    ELEFT2=THEVAL(I)*.1
      ELEFT1=ELEFT1-(ELEFT2*ZVAL(I))
      THEVAL(I)=.1
19    CONTINUE
C
C
C
2. DO 29 I=1,4
      IF (TVAL(I).EQ.0.0) GO TO 29
      IF (THEVAL(I).LE.THEMIN(I)) GO TO 21
      TCK=THEVAL(I)-(TVAL(I)/ZVAL(I))
      IF (TCK.LT.THEMIN(I)) GO TO 22
      THEVAL(I)=TCK
      GO TO 29
21    TVAL(I+1)=TVAL(I+1) + TVAL(I)
      TVAL(I)=0.0
      GO TO 29
22    RMD=THEVAL(I)-THEMIN(I)
      TVAL(I+1)=TVAL(I+1)+(TVAL(I)-(RMD*ZVAL(I)))
      TVAL(I)=RMD*ZVAL(I)
      THEVAL(I)=THEMIN(I)
29    CONTINUE
C
C
C
      THEVAL(5)=THEVAL(5)-(TVAL(5)/ZVAL(5))
C
      RETURN
      END
      SUBROUTINE CAY2(THEVAL,IRRIG,ZVAL,RUNOFF,CD,THEMAX)
      DIMENSION THEVAL(5),ZVAL(5),THEMAX(5)

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REAL IRRIG;
INTEGER: CD(5);
R=IRRIG;
DO, 1 I=1,3
  CK=(.5-THEVAL(I))*ZVAL(I);
  IF(R.LT.CK) GO TO 2;
  THEVAL(I)=.5;
  CD(I)=2;
  R=R-CK;
1 CONTINUE;
RUNCFF=R+RUNCFF;
GO TO 3;
2 THEVAL(I)=THEVAL(I)+R/ZVAL(I);
  IF (THEVAL(I).GT.TFEMAX(I)) CD(I)=2;
3 RETURN;
END;

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